rate. Kolb and Scheraga explain the rationale for calculating the social costs of compliance using this 2-stage discounting approach.[140]

A second important assumption in the economic analysis is that publicly owned landfills have more flexibility in generating the revenues to pay for the capital and operating costs of emissions controls than privately owned landfills. Specifically, public entities can generate the revenues for compliance costs by increasing taxes of various types or by increasing user fees at the landfill while it is still accepting MSW. Alternatively, private landfills can only cover compliance costs by increas-ing user fees during the landfill's operating life.*

The difference in public and private landfills regarding their ability to generate the revenues for covering the costs of emissions controls has important implications for the annualization period for such costs. In particular, we annualize the enterprise costs for publicly owned landfills over the control period. Even though the landfill will be closed during some of the control period, the public entity that owns the landfill will still be able to tax former users of the landfill (and possibly others) in order to cover the compliance costs. Alternatively, we annualize enterprise costs for privately owned existing landfills over the period from 1992 (the anticipated promulgation date of the regulatory alternative selected) to the landfill's closure date.† We assume that these landfills must sufficiently increase user fees during this time period to cover compliance costs over the entire control period (including the years after closure). Thus, the necessary increase in user fees may be quite large whenever compliance costs are relatively high and the number of years until closure is relatively small.

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*The difference in the ability of public versus private landfills to generate revenues for compliance costs is particularly significant for affected landfills that are closed before the regulations are promulgated. Public entities that own a closed landfill can increase taxes on households and businesses that were previously served by the closed landfill in order to pay for emissions controls. Owners of private landfills that are closed have no way to generate revenues to cover the costs of emissions controls.

†We annualize enterprise costs for privately owned new landfills over the entire operating life of these landfills.

8.4 ANALYSIS OF ECONOMIC IMPACTS

As described in Section 8.3, the EPA is considering regulatory alternatives for controlling air emissions from both closed/existing landfills and new landfills. Section 8.4 first discusses the economic impacts of the three possible nonmethane organic compound (NMOC) emissions level cutoffs under the Guidelines of §111(d) of the Clean Air Act (CAA). Then, this section discusses the economic impacts of proposed regulations under the Standards of CAA §111(b) for the same three possible NMOC emissions level cutoffs. In evaluating the impacts of controls under each section of the CAA, we consider two basic control options: combustion without energy recovery (the flare option), and energy recovery (the energy recovery option).

As described above, increasing NMOC emissions cutoffs (i.e., 25 Mg NMOC/yr, 100 Mg NMOC/yr, and 250 Mg NMOC/yr) represent decreasing levels of stringency for the controls. Thus, for example, more landfills are affected by each control option at the 25 Mg level than at the 100 Mg level. Landfills will be required to operate controls in every year for which their emissions level exceeds the chosen cutoff level. So some landfills may need to operate controls for many years after closure, until the NMOC emissions fall below the chosen cutoff level.

8.4.1 Section 111(d) Guidelines

Guidelines under §111(d) of the CAA address existing sources of emissions. In the case of landfills, these guidelines will apply to both closed and existing landfills, since the level of NMOC emissions builds throughout the active life of a landfill and continues after closure. As indicated in Section 8.3, the model used to estimate emissions assumes that each landfill that closes is replaced by another identical landfill serving the same area.

We first characterize the landfills affected under each stringency level for the flare option, then we address the economic impacts of the stringency levels on affected landfills. Next, we examine the energy recovery option, characterizing the affected landfills under each stringency level and estimating the economic impacts of that option.

8.4.1.1 Flare Option. Under the flare option, landfills are assumed to control their NMOC emissions by collecting the NMOCs and then burning

them, with no provision for energy recovery. We assume that all landfills generating NMOC emissions above a given stringency level are affected by the §111(d) Guideline. As mentioned above, three possible stringency levels are being evaluated: 25 Mg NMOC/yr, 100 Mg NMOC/yr, and 250 Mg NMOC/yr.

Of 7124 landfills (6034 existing landfills and 1090 closed landfills) eligible for coverage under the §111(d) Guidelines, between 5% and 26% of the landfills would be affected, depending on the stringency level selected. As indicated in Table 8-6, if the most stringent 25 Mg NMOC/yr cutoff were selected, 1884 landfills would be affected. If the 100 Mg NMOC/yr stringency level were selected, 853 landfills would be affected, while only 386 landfills would be affected if the 250 Mg NMOC/yr stringency level were selected.

In addition to the total number of affected landfills, Table 8-6 shows a distribution of affected landfills by design capacity under each of the possible stringency levels. Under the most stringent 25 Mg stringency level, a larger proportion of the total number of affected landfills is small (27% have less than 1 million Mg design capacity, 71% have less than 5 million Mg design capacity) than under the less stringent cutoff levels. Only 16% of the affected landfills would have a design capacity below 1 million Mg under the 100 Mg stringency level, while only 6% would fall into this smallest size category under the least stringent 250 Mg cutoff level.

As mentioned above, some landfills will be required to operate emissions controls for many years after they close. This is of particular concern for private landfills, since increased user fees while they are still active and accepting MSW are their only means of paying for these controls. The bottom part of Table 8-6 shows the number of affected privately owned landfills under each stringency level. The landfills expected to have the greatest difficulty paying for the NMOC controls are those which are privately owned and already closed. For these landfills, there exists no possibility of recovering the costs of compliance through increased user fees. As shown by the last line, 4% of the affected landfills under the most stringent 25 Mg level are privately owned closed landfills. Under the 100 Mg stringency level, 6% of the affected landfills

TABLE 8-6. SUMMARY INFORMATION FOR AFFECTED CLOSED AND EXISTING LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
Number of affected landfills	**1,884**	**853**	**386**
(Percent of total closed and existing landfills)	(26)	(12)	(5)
Distribution of affected landfills by design capacity (10^6 Mg)			
≤ 1	**514**	**133**	**22**
	(27)	(16)	(6)
1 to 5	**837**	**349**	**181**
	(44)	(41)	(47)
5 to 10	**295**	**176**	**48**
	(16)	(21)	(12)
> 10	**238**	**195**	**135**
	(13)	(23)	(35)
Total	**1,884**	**853**	**386**
	(100)	(100)	(100)
Privately owned affected landfills	**406**	**210**	**121**
(Percent of affected landfills)	(22)	(25)	(31)
Existing	**334**	**162**	**82**
Closed	**72**	**48**	**39**

Note: The numbers in parentheses are percentages. Details may not add to totals due to rounding.

are privately owned closed landfills, while under the 250 Mg level, 10% are privately owned and closed.

As noted earlier, landfills will be required to operate emissions controls as long as their NMOC emissions exceed the selected cutoff level. In general, different landfills will reach a given emissions cutoff level in different years. Similarly, the number of years that emissions will exceed the cutoff level will vary from landfill to landfill, and therefore the year that controls may be removed will vary from landfill to landfill. Thus, the possible economic impacts of the emissions controls will be incurred by various landfills during different time periods.

Table 8-7 depicts the distribution of the length of the control period for affected closed and existing landfills under each of the three stringency levels. In general, the control periods range from one to more than 277 years, with the maximum length of control period being slightly longer as the stringency of control increases. The average length of control period ranges from 66 years for the 100 Mg stringency level to 79 years for the 25 Mg stringency level.

As mentioned above, the ease with which landfills will be able to recapture the costs of installing and operating the controls will decrease after the landfill closes. Until that time, the landfill may increase its user fees to offset some of its increased costs. After closure, the public owners of the landfill will have to find some other means of raising revenues (such as taxes), while the private owners will not be able to raise revenues at all. Private landfills must therefore increase user fees sufficiently to offset all their control costs while the landfill is still accepting MSW. Thus, the shorter the length of time between the start of controls and landfill closure, the greater the financial burden of a given control cost on a landfill, especially if it is privately owned.

Table 8-8 provides information about the length of control period prior to closure for all affected closed and existing landfills, and 8-9 provides such information for privately owned affected landfills. The 22% to 23% of affected landfills that are privately owned under the 25 Mg and 100 Mg stringency levels, respectively, have slightly longer control periods prior to closure than the publicly owned affected landfills, while the 27% of affected landfills which are privately owned under the 250 Mg

TABLE 8-7. LENGTH OF CONTROL PERIOD FOR AFFECTED CLOSED AND EXISTING LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
Average length of control period (years)	79.2	66.3	67.8
Distribution of affected landfills by length of control period (years)			
≤ 25	298 (16)	244 (29)	94 (24)
26 to 50	305 (16)	165 (19)	46 (12)
51 to 100	607 (32)	229 (27)	150 (39)
101 to 150	582 (31)	157 (18)	80 (21)
> 150	92 (5)	58 (7)	16 (4)
Total	1,884 (100)	853 (100)	386 (100)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE 8-8. LENGTH OF CONTROL PERIOD PRIOR TO CLOSURE FOR AFFECTED EXISTING LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
Average length of control period prior to closure (years)	**20.4**	**17.7**	**19.7**
Distribution of affected landfills by length of control period prior to closure (years)			
≤ 5	**370** (24)	**239** (34)	**94** (31)
6 to 10	**244** (16)	**99** (14)	**29** (10)
11 to 20	**513** (34)	**227** (33)	**106** (35)
21 to 50	**261** (17)	**63** (9)	**41** (13)
> 50	**133** (9)	**70** (10)	**32** (11)
Total	**1,521** (100)	**698** (100)	**302** (100)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding. Excludes closed landfills.

TABLE 8-9. LENGTH OF CONTROL PERIOD PRIOR TO CLOSURE FOR AFFECTED EXISTING LANDFILLS: PRIVATE LANDFILLS ONLY

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
Average length of control period prior to closure (years)	**23.0**	**20.1**	**17.0**
Distribution of affected landfills by length of control period prior to closure (years)			
≤ 5	**73** (22)	**56** (35)	**22** (27)
6 to 10	**39** (11)	**17** (10)	**10** (12)
11 to 20	**130** (39)	**53** (33)	**29** (35)
21 to 50	**46** (14)	**19** (12)	**19** (23)
> 50	**46** (14)	**17** (10)	**2** (3)
Total	**334** (100)	**162** (100)	**82** (100)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding. Excludes closed landfills.

stringency level have a slightly shorter control period prior to closure. Of particular concern may be the privately owned landfills with ten years or less between the imposition of controls and closure. These comprise 112 of the privately owned affected landfills under the 25 Mg stringency level, 73 under the 100 Mg stringency level, and 32 under the 250 Mg stringency level.

One measure of the cost of complying with the regulatory alternatives under consideration is the net present value of enterprise costs. This measure, shown in Table 8-10, is computed by discounting the flow of capital and operating costs to arrive at a measure of the current value of the costs that will be incurred throughout the control periods for the various landfills. Since most landfills will begin and end controls at different times, using a net present value measure of costs is the appropriate way to compare costs between landfills.

As explained in Section 8.3, the interest rates faced by public owners of landfills differ from those faced by private owners, so we discount the stream of capital and operating costs using a different discount rate for each ownership group. We discount the capital and operating costs incurred by public landfill owners as a result of complying with the regulatory alternatives under consideration using a 4% discount rate, while we discount costs incurred by private landfill owners to their present value using an 8% discount rate. Table 8-10 presents these costs, along with a distribution of the number of affected landfills in several enterprise cost categories for each of the three stringency levels.

The maximum net present value (NPV) of enterprise costs incurred by any landfill is $61 million under the 25 Mg stringency level, $54 million under the 100 Mg stringency level, and $51 million under the 250 Mg stringency level. When summed across all landfills affected by controls under each stringency level, the national total NPV of enterprise costs ranges from $1.93 billion under the 250 Mg stringency level to $5.86 billion under the 25 Mg stringency level (see Table 8-10). A larger proportion of affected landfills incurs a relatively low NPV of enterprise costs ($3 million or less) under the 25 Mg level than under the 100 Mg level or the 250 Mg level. The mean NPV of enterprise costs per affected landfill under the 250 Mg stringency level, $5.00 million, exceeds that for the other two stringency levels.

TABLE 8-10. NET PRESENT VALUE OF ENTERPRISE COSTS FOR AFFECTED CLOSED AND EXISTING LANDFILLS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National enterprise costs (10^6)			
Capital	2,233	1,618	871
Operating	3,625	2,015	1,058
Total	5,858	3,634	1,929
Average total enterprise cost per affected landfill (10^6)	3.11	4.26	5.00
Distribution of affected landfills by net present value of enterprise costs (10^6)			
≤ 0.5	119	60	15
	(6)	(7)	(4)
0.5 to 1.0	165	90	19
	(9)	(11)	(5)
1.0 to 3.0	1,060	341	169
	(56)	(40)	(44)
3.0 to 5.0	331	205	101
	(18)	(24)	(26)
5.0 to 10.0	161	111	53
	(8)	(13)	(14)
>10.0	48	46	29
	(3)	(5)	(7)
Total	1,884	853	386
	(100)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of enterprise cost is calculated using a 4 percent discount rate for publicly owned landfills and an 8 percent discount rate for privately owned landfills. Details may not add to totals due to rounding.

Table 8-11 shows another measure of enterprise costs. The annualized enterprise control cost per Mg of MSW for affected existing landfills is computed based on each landfill's NPV of enterprise costs. These costs are annualized using the following formula:

$$\frac{\text{NPV enterprise costs}}{(1 - (1+r)^{-t})/r}$$

where r is the interest rate and t is time.

The interest rate and the length of time over which costs are annualized depend on the ownership of the landfill. As explained previously, publicly owned landfills are annualized using a 4% interest rate over the time period during which controls will be in place. Privately owned landfills, on the other hand, will not be able to recapture their compliance costs after they stop accepting MSW. The enterprise costs for privately owned landfills, therefore, are annualized over the period from 1992 until the landfill closes, using an 8% interest rate.

To compute the annualized enterprise cost per Mg of MSW for affected existing landfills, the annualized cost is divided by the quantity of waste accepted by the landfill in 1986.* One measure of the average annualized cost per Mg of waste accepted is the national annualized cost per Mg of MSW, which is computed for each stringency level by summing the annualized enterprise costs for all the affected landfills at that level, and then dividing by the summed quantities of waste accepted by all the affected landfills in 1986. The national average annualized costs per Mg of MSW at each stringency level is less than $1 per Mg. These national annualized costs per Mg of MSW range from $0.72/Mg at the 250 Mg stringency level to $0.89/Mg at the 25 Mg level.

Table 8-11 also contains a frequency distribution of affected landfills by annualized cost per Mg of MSW accepted in 1986. The frequency distribution indicates that the proportion of affected landfills incurring annualized costs of $1.25 per Mg of MSW or less increases as the level of stringency decreases. At the 25 Mg stringency level, about 45% of

*As noted in Section 8.3, the historical annual average amount of MSW accepted by the landfill is substituted for the quantity of MSW received in 1986 for some landfills.

TABLE 8-11. ANNUALIZED ENTERPRISE CONTROL COST PER Mg OF MSW FOR AFFECTED EXISTING LANDFILLS

	Stringency Level (Mg NMOC/yr)		
	25	100	250
National annualized cost per Mg MSW ($/Mg MSW)	0.89	0.84	0.72
Distribution of affected landfills by annualized cost per Mg MSW ($/Mg MSW)			
≤ 0.50	207 (14)	135 (19)	77 (25)
0.50 to 1.25	474 (31)	220 (32)	106 (35)
1.25 to 3.00	426 (28)	206 (30)	92 (30)
3.00 to 10.00	320 (21)	123 (18)	27 (9)
> 10.00	94 (6)	14 (2)	0 (0)
Total	1,521 (100)	698 (100)	302 (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent from 1992 to the year of closure. Details may not add to totals due to rounding. Excludes closed landfills.

landfills experience annualized costs of $1.25 per Mg or less; the maximum annualized cost at this level of stringency, however, is $57 per Mg. At the 100 Mg stringency level the maximum annualized cost falls to $25 per Mg of MSW, and the proportion experiencing costs of $1.25 per Mg or less increases to 51%. Finally, at the 250 Mg stringency level, 60% of affected landfills experience annualized costs per Mg of MSW of $1.25 or less, and the maximum annualized cost experienced is only $8 per Mg.

As noted above, the enterprise costs for privately owned landfills are annualized over a period beginning when the regulation takes effect in 1992 and ending when the landfill closes. Privately owned landfills can only recapture their costs through increased user fees while they are still accepting MSW. The shorter the period of time between 1992 and the year the landfill closes, therefore, the greater the potential burden of a particular amount of control costs on the landfill's owners. Tables 8-12 and 8-13 give the same information as Table 8-11, but for privately owned landfills which have five or fewer years until closure or 5 to 10 years until closure, respectively. Table 8-12 shows that the national annualized enterprise cost per Mg of MSW accepted for private landfills with five years or less until closure is more than five times the national annualized costs for all affected landfills at each stringency level. Specifically, at the 250 Mg stringency level, the national annualized enterprise cost is $5.33 per Mg of MSW, it is $4.37 per Mg of MSW at the 100 Mg level, and it is $5.24 per Mg at the 25 Mg stringency level. At the 100 Mg stringency level, 90% of the 41 affected landfills that are expected to close by 1997 experience annualized costs between $3.00 and $10.00 per Mg of MSW.

For private landfills closing between 1998 and 2002, unit control costs are not nearly as high as the unit control costs of private landfills closing before 1988 (see Table 8-13). The national average measure is $1.17/Mg of MSW at the 25 Mg stringency level, $0.95/Mg of MSW at the 100 Mg stringency level, and only $0.48/Mg at the 250 Mg stringency level. At the 250 Mg stringency level, only two landfills affected are expected to close between 5 and 10 years after 1992, and they incur costs less than $0.50 per Mg of MSW. At the 100 Mg stringency level, only 7 affected landfills are expected to close between 1998 and 2002, and they experience annualized enterprise costs between $0.50/Mg and $1.25/Mg. At the 25 Mg

TABLE 8-12. ANNUALIZED ENTERPRISE CONTROL COST PER Mg OF MSW FOR AFFECTED EXISTING LANDFILLS WITH DATE OF CLOSURE BEFORE 1998: PRIVATE LANDFILLS ONLY

	Stringency Level (Mg NMOC/yr)		
	25	100	250
National annualized cost per Mg MSW ($/Mg MSW)	**5.24**	**4.37**	**5.33**
Distribution of affected landfills by annualized cost per Mg MSW ($/Mg MSW)			
≤ 0.50	**0** (0)	**0** (0)	**0** (0)
0.50 to 1.25	**2** (4)	**2** (5)	**0** (0)
1.25 to 3.00	**2** (4)	**2** (5)	**2** (14)
3.00 to 10.00	**39** (67)	**37** (90)	**12** (86)
> 10.00	**15** (26)	**0** (0)	**0** (0)
Total	**58** (100)	**41** (100)	**14** (100)

Note: Numbers in parentheses are percentages. Costs for privately owned landfills are annualized at 8 percent from 1992 to the year of closure. Details may not add to totals due to rounding. Excludes closed landfills.

TABLE 8-13. ANNUALIZED ENTERPRISE CONTROL COST PER Mg OF MSW FOR AFFECTED EXISTING LANDFILLS DATE OF CLOSURE BETWEEN 1998 AND 2002: PRIVATE LANDFILLS ONLY

	Stringency Level (Mg NMOC/yr)		
	25	**100**	**250**
National annualized cost per Mg MSW ($/Mg MSW)	**1.17**	**0.95**	**0.48**
Distribution of affected landfills by annualized cost per Mg MSW ($/Mg MSW)			
≤ 0.50	**0** (0)	**0** (0)	**2** (100)
0.50 to 1.25	**10** (59)	**7** (100)	**0** (0)
1.25 to 3.00	**0** (0)	**0** 0	**0** (0)
3.00 to 10.00	**7** (41)	**0** (0)	**0** (0)
> 10.00	**0** (0)	**0** (0)	**0** (0)
Total	**17** (100)	**7** (100)	**2** (100)

Note: Numbers in parentheses are percentages. Costs for privately owned landfills are annualized at 8 percent from 1992 to the year of closure. Details may not add to totals due to rounding. Excludes closed landfills.

level, 17 landfills are expected to close between 1998 and 2002, with annualized costs between $0.50/Mg and $10.00/Mg.

Table 8-14 presents the annualized enterprise cost per household for affected existing landfills. This attempts to assess the annualized cost that will be borne by households served by affected landfills. To compute this measure, the annualized enterprise costs are divided by an estimated number of households served by the affected landfills.* The national annualized enterprise cost per household for each stringency level is computed by summing the annualized enterprise costs incurred by all affected landfills at that stringency level, and then dividing by an estimate of the total number of households served by those landfills in 1986. The national annualized enterprise cost ranges from $4.16 per household at the 250 Mg stringency level to $5.18 per household at the 25 Mg stringency level. At the intermediate 100 Mg stringency level, the national annualized enterprise cost is $4.90 per household.

The frequency distribution of affected landfills by annualized enterprise cost per household, also shown in Table 8-14, indicates that one-fifth of affected landfills at the 25 Mg stringency level will incur annualized enterprise costs of $3.50 per household or less, and 43% will incur annualized enterprise costs of $7.00 per household or less, although the maximum annualized cost at this stringency level is $332 per household. At the 100 Mg stringency level, the maximum annualized cost incurred is $148 per household; however, one-quarter of the affected landfills will incur annualized costs of $3.50 per household or less and one-half will incur costs of $7.00 per household or less. Only 10% of affected landfills will incur annualized costs of $30.00 per household or more under the 100 Mg stringency level. At the 250 Mg stringency level, over one-third of

*We estimated the number of households served by affected landfills using the amount of MSW received by these landfills and an average amount of MSW generated by households. We calculated the latter by dividing the total amount of MSW going to all landfills based on the OSW data by the estimated number of households served by landfills in the United States. This resulted in a much higher MSW generation rate per household than other estimates, but this MSW generation rate is consistent with the MSW acceptance rates used in the cost model. Nevertheless, these MSW generation rates per household probably result in overestimates of annualized enterprise costs per household served by affected landfills.

TABLE 8-14. ANNUALIZED ENTERPRISE CONTROL COST PER HOUSEHOLD FOR AFFECTED EXISTING LANDFILLS

	Stringency Level (Mg NMOC/yr)		
	25	**100**	**250**
National annualized cost per household ($/Household)	**5.18**	**4.90**	**4.16**
Distribution of affected landfills by annualized cost per household ($/Household)			
≤ 3.50	**313** (21)	**190** (27)	**108** (36)
3.50 to 7.00	**336** (22)	**164** (23)	**75** (25)
7.00 to 15.00	**407** (27)	**184** (26)	**85** (28)
15.00 to 30.00	**216** (14)	**87** (12)	**15** (5)
> 30.00	**249** (16)	**73** (10)	**19** (6)
Total	**1,521** (100)	**698** (100)	**302** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent from 1992 to the year of closure. Details may not add to totals due to rounding. Excludes closed landfills.

the affected landfills experience annualized costs per household of $3.50 or less and 61% incur costs of $7.00 per household or less.

A measure of the potential cost to society of complying with the regulatory alternatives is the net present value of social costs. This measure, shown in Table 8-15, is computed by first annualizing capital costs and then discounting the flow of capital and operating costs to arrive at a measure of the present value of the costs that will be incurred throughout the control periods for the various landfills. A net present value measure of costs is the appropriate way to compare costs between landfills since most landfills will begin and end controls at different times.

As noted in Section 8.3, computing the net present value of social costs involves a two-stage process. First, the capital costs, which are incurred in discrete "lumps" periodically throughout the control period, are annualized over the control period using a 10% rate. Then the resulting stream of annualized capital costs and the stream of annual operating costs are discounted using a 3% discount rate. These costs are combined to yield the total net present value (NPV) of social costs incurred by each affected landfill. The maximum NPV of social costs incurred by any landfill is $140 million under the 25 Mg stringency level, $112 million under the 100 Mg stringency level, and $75 million under the 250 stringency level.

When summed across all affected landfills under each stringency level, the national total NPV of social costs ranges from $3.92 billion under the 250 Mg stringency level to $11.65 billion under the 25 Mg stringency level (see Table 8-15). While more landfills are affected under the more stringent 25 Mg level than under the other two stringency levels, a larger proportion of affected landfills incurs relatively lower NPV of social costs ($3 million or less) under the 25 Mg level than under the 100 Mg level or the 250 Mg level. The mean NPV of social costs per affected landfill under the 250 Mg stringency, $10.1 million, exceeds the mean NPV of social costs for the other two stringency levels.

Annualizing the net present value of social costs provides another measure of the cost to society of the regulatory alternatives under consideration. In this situation we annualized the net present value of the social cost of each affected landfill over the years from 1992 to the

TABLE 8-15. NET PRESENT VALUE OF SOCIAL COSTS FOR AFFECTED CLOSED AND EXISTING LANDFILLS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National social costs (10^6)			
Capital	6,438	4,326	2,403
Operating	5,213	2,831	1,514
Total	11,651	7,157	3,917
Average total social cost per affected landfill (10^6)	6.18	8.39	10.1
Distribution of affected landfills by net present value of social costs (10^6)			
≤ 0.5	31	29	7
	(2)	(3)	(2)
0.5 to 1.0	97	24	7
	(5)	(3)	(2)
1.0 to 3.0	654	206	61
	(35)	(24)	(16)
3.0 to 5.0	421	189	92
	(22)	(22)	(24)
5.0 to 10.0	464	261	137
	(25)	(31)	(35)
>10.0	217	144	82
	(11)	(17)	(21)
Total	1,884	853	386
	(100)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of social cost is computed using a two-step discounting procedure. First, capital costs are annualized at 10 percent over the control period. Then, present values are computed by discounting annual operating costs and annualized capital costs at 3 percent. Details may not add to totals due to rounding.

end of the landfill's control period using a 3% discount rate, and then we summed these individual annualized values to get the total annualized social cost. The resulting total annualized social cost for affected closed and existing landfills for each stringency level is:

- $416 million for the 25 Mg stringency level
- $297 million for the 100 Mg stringency level
- $150 million for the 250 Mg stringency level.

Thus, the annualized social cost of the 100 Mg stringency level is almost twice the annualized social cost of the 250 Mg stringency level. The annualized social cost of the 25 Mg stringency level is 40% higher than the annualized social cost for the 100 Mg stringency level.

8.4.1.2 Energy Recovery Option. As discussed in Section 8.3, it will be more economical for some landfills to reduce emissions by using flares, while for others it will be more economical to use an energy recovery technique. While energy recovery is more costly, especially in terms of initial capital investment, it also will bring in some revenue from the sale of the purified landfill gas or the energy produced from various uses of this gas. In considering the energy recovery options, we omit the landfills that would actually profit from energy recovery according to the model in Chapter 7, because we assume these landfills would initiate the use of energy recovery even in the absence of EPA emissions control regulations. We therefore conclude that neither the emissions reductions nor the costs of emissions control with energy recovery at these landfills should be attributed to the regulatory alternatives under consideration. So assessing the impacts of these regulatory alternatives involves studying only those landfills that would experience positive costs using the least costly control option.

When we omit all landfills that would find energy recovery profitable (that is, landfills where the revenue from energy recovery exceeds the energy recovery costs), the number of affected landfills at each potential level of stringency is considerably smaller. As Table F-1 in Appendix F shows, the number of affected landfills falls from 1884 to 1024, a decrease of 46% under the most stringent regulatory alternative (i.e., 25 Mg of NMOC/yr). At the 100 Mg stringency level, the number of affected landfills

falls by 62%, from 853 to 325. Finally, at the least stringent 250 Mg level, the number of affected landfills falls by 80%, from 386 to only 77.

Table F-1 also shows the number of privately owned affected landfills under the energy recovery option. As described above, privately owned landfills may have the greatest difficulty paying for the emissions controls, because all their costs must be recaptured through increased user fees during the period when the landfill is still actively accepting MSW. The number of privately owned affected landfills varies from 27 under the least stringent 250 Mg cutoff to 68 under the 100 Mg stringency level, and 215 under the 25 Mg stringency level. From 10 to 29 of the privately owned landfills will close by 1992 and therefore are expected to have no way of recapturing the costs of compliance.

As described above, landfills must use emissions controls during a control period that will vary in length from landfill to landfill, extending beyond the closure of the landfill. Table F-2 depicts the length of control period, while F-3 shows the length of control period prior to closure. Although the control period may be as long as 130 years under the 250 Mg stringency level, 235 years under the 100 Mg stringency level, and 277 years under the 25 Mg stringency level, the average length of the control period is much shorter. The average control period for affected landfills under the 250 Mg stringency level is 36 years, while it is 51 years under the 100 Mg stringency level, and it is 70 years under the 25 Mg stringency level. Also, as shown in the frequency distribution of affected landfills by length of control period, the proportion of affected landfills with control periods less than, for example, 50 years, is roughly two-thirds under the 250 Mg and 100 Mg stringency levels, but is only 43% under the 25 Mg stringency level.

The shorter the time between the imposition of controls and a landfill's closure, the more difficult it will be for the landfill to recover a given amount of compliance costs by increasing user fees at the landfill. This problem, of course, is particularly serious for landfills which are already closed, but it may also affect landfills with a fairly short period of time (for example, only 5 or 10 years) between the start of the controls and the landfill's closure. Table F-3 shows the length of the control period prior to closure for existing landfills under the energy recovery

option. While some landfills have as much as 177 years of operating life under the 25 Mg stringency level, the average length of control period prior to closure for that stringency level is about 21 years. For the less stringent levels, the average operating lives are even shorter--14.5 years for the 100 Mg stringency level and less than 9 years for the 250 Mg stringency level. A larger share of the affected landfills will have shorter control periods before closure at the less stringent 250 Mg and 100 Mg levels of control than at the most stringent 25 Mg level. At the 250 Mg stringency level, 81% have 10 years or less of controls prior to closure, while 63% have ten years or less prior to closure at the 100 Mg stringency level, and 41% have 10 years or less prior to closure at the 25 Mg stringency level.

To measure the impacts of the regulatory alternatives under consideration on the owners of landfills, we use the net present value (NPV) of enterprise costs. These costs include both capital investments and operating costs, less revenues from energy recovery for those landfills that choose the energy recovery option. Table F-4 shows these costs, along with a frequency distribution of landfills by NPV of enterprise costs. We assume that the landfill will choose the control option that minimizes its costs of control. To determine which option a particular landfill will select, we discount the capital and operating costs incurred over time to compute a NPV of each. For publicly owned landfills, we use a 4% discount rate, while for privately owned landfills we use an 8% discount rate. The NPV of enterprise costs for the flare control option for each landfill is compared with the NPV of enterprise costs for the energy recovery option minus the revenue from the energy recovery activity.

Allowing landfills to employ an energy recovery control option has two overall effects on the impacts of the regulation. First, fewer landfills are affected, because we assume that any landfill for which the energy recovery option is profitable would have instituted such a system in the absence of any EPA emissions regulation. Thus, we can attribute neither the emissions reductions nor the costs of installing and operating energy recovery equipment to the regulatory alternatives under consideration. Second, the remaining landfills incur lower enterprise costs, both in the aggregate and on average. As just noted, the number of landfills affected

by the regulation falls for each stringency level. As a result, we would expect aggregate NPV of enterprise costs to be lower, even if the average NPV of enterprise costs per landfill did not decrease. In fact, however, the average NPV of enterprise costs per landfill does decrease, falling 54% to 68% when we allow landfills to choose the least costly control option (see Table F-4). At the 100 Mg stringency level, for example, the average NPV of enterprise costs per landfill under the flare option is $4.26 million. When the landfills are allowed to choose their least costly control option, the average landfill now only incurs an NPV of enterprise costs of $1.39 million. As a result of these combined trends, the aggregate NPV of enterprise cost falls by 75% and 93%, depending on the stringency level. The frequency distribution of affected landfills by NPV of enterprise costs is even more skewed toward the lower cost categories under the energy recovery option than under the flare option. At the 25 Mg stringency level, for example, 71% of landfills incur NPV of enterprise costs less than $3 million under the flare option, while 93% of landfills incur NPV of enterprise costs less than $3 million under the energy recovery option.

Annualized enterprise cost is another measure of the impacts of enterprise costs on landfill owners. This is computed for publicly owned landfills by annualizing the NPV of enterprise costs for each landfill using a 4% interest rate over the period during which controls are in place for that landfill. Costs for privately owned landfills are computed by annualizing the NPV of enterprise costs for each landfill using an 8% interest rate over the period from 1992 through the year when the landfill closes.

Table F-5 displays the annualized enterprise costs per Mg of MSW for landfills having positive energy recovery costs. This is computed by dividing the NPV of enterprise costs by the reported quantity of waste accepted in 1986. The national annualized cost per Mg of MSW accepted is computed by summing annualized enterprise cost for all the affected landfills under each stringency level, and then dividing by the sum of the reported quantities of waste accepted by all affected landfills in 1986. These quantities range from $1.43/Mg of MSW accepted at the 250 Mg stringency level to $2.66/Mg of MSW at the 100 Mg stringency level. The

national annualized cost per Mg of MSW for the 25 Mg stringency level falls between those values, at $1.64/Mg of MSW accepted. Although these costs are low, they are about two to three times higher than the national annualized enterprise costs per Mg of MSW under the flare option (see Table 8-11). This occurs because many of the affected landfills with low enterprise costs per Mg of MSW under the flare option will make a profit from energy recovery. So these low unit cost landfills are omitted from the group of affected landfills under the energy recovery option.

Table F-5 also shows a frequency distribution of affected landfills by annualized cost per Mg of MSW. The proportion of affected landfills experiencing annualized costs exceeding $3.00 per Mg is 43% under both the 25 Mg stringency level and the 100 Mg stringency level; the maximum annualized cost incurred at the 25 Mg level is $57.15 per Mg, while the maximum is $25.42 per Mg at the 100 Mg level. At the 250 Mg stringency level, the proportion of landfills with annualized costs of $3.00 per Mg or more falls to 24%, and the maximum annualized cost is $8.39.

We measure the impacts of the §111(d) regulatory alternatives under consideration on the users of affected landfills with the annualized enterprise cost per household. This is computed by dividing the annualized enterprise cost by the estimated number of households (based on an average waste generation rate per household) served by the landfill. The national annualized cost per household, shown at the top of Table F-6, is computed by summing the annualized enterprise costs for each affected landfill at each stringency level, and then dividing by the sum of the estimated number of households served by all the affected landfills at that stringency level. The national annualized cost per household varies from $8.33 per household at the 250 Mg stringency level, to $9.50 at the 25 Mg stringency level, to $15.47 at the 100 Mg stringency level. As was the case for annualized costs per Mg of MSW, national annualized household costs under the energy recovery option are much higher than the annualized household costs under the flare option, because many of the low household cost landfills are not affected by the regulatory alternatives under the assumptions of the energy recovery option.

The frequency distribution of affected landfills by annualized cost per household suggests that the 821 affected landfills at the 25 Mg

stringency level incur annualized costs per household that are more concentrated at the lower values ($7.00 per household or less) than the costs incurred by the 252 affected landfills at the 100 Mg level. The national average cost per household at the 100 Mg stringency level is about $15, but one-quarter of affected landfills at this level incur annualized costs of $30 per household or more.

The net present value of social costs in Table F-7 measures the potential impacts of the stringency levels under consideration on society. The capital costs of compliance are annualized at a 10% rate, then the resulting stream of annualized capital costs plus operating costs are discounted at a 3% rate to determine the net present value of these costs. The NPV of revenues from energy recovery then are subtracted from total costs for those landfills that use the energy recovery option. As indicated in Table F-7, the national social cost of the regulatory alternatives ranges from $253 million for the least stringent 250 Mg level of control to $2.96 billion for the most stringent 25 Mg level of control. While aggregate costs are higher at the more stringent levels of control, average social cost per landfill is lower, because more landfills with lower costs are affected. Specifically, the average total social cost per affected landfill is $2.89 million at the 25 Mg stringency level, $2.55 million at the 100 Mg stringency level, and $3.27 million at the 250 Mg level.

To provide another perspective on the social cost of the regulatory alternatives under consideration, we calculated the annualized social cost for the three stringency levels for the energy recovery option. Specifically, we annualized the net present value of social cost for each landfill over the years from 1992 to the end of its control period using a 3% discount rate, and then we summed the individual annualized values to estimate the total annualized social cost. These costs are:

- $124 million for the 25 Mg stringency level
- $68 million for the 100 Mg stringency level
- $19 million for the 250 Mg stringency level.

Note that annualized social cost exceeds $100 million only for the most stringent regulatory alternative under the energy recovery option. Furthermore, these annualized social costs are much lower than the

annualized social cost of the three stringency levels under the flare option. Specifically, the annualized social cost of the 100 Mg stringency level under the energy recovery option ($68 million) is just one-fourth of the annualized social cost of this same stringency level under the flare option ($297 million).

8.4.2 Section 111(b) Standards

The §111(b) Standards apply to landfills constructed and opened after 1992 when the regulation takes effect. In our case, we assume these new landfills are replacing other landfills that closed. Specifically, we assume that every landfill that closes after 1992 is replaced by an identical landfill serving the same area.

8.4.2.1 Flare Option. Of 944 new landfills nationwide, there are 41 affected by the flare option at the 250 Mg stringency level, 104 affected by the flare option at the 100 Mg stringency level, and 247 affected by the flare option at the 25 Mg stringency level. Tables 8-16 through 8-18 provide information on these affected landfills.

Table 8-16 shows the number of affected new landfills, along with the number of such landfills which are privately owned. As with the closed/existing landfills, privately owned new landfills will need to recapture the costs of compliance with the regulation while they are still accepting MSW. At the 25 Mg level of stringency, 51 of the affected landfills are privately owned, 24 are privately owned at the 100 Mg stringency level, while 14 are privately owned at the 250 Mg stringency level. Table 8-16 also shows a frequency distribution of affected new landfills by design capacity. At the most stringent 25 Mg cutoff level the majority of affected landfills have less than 5 million Mg of capacity, while at the less stringent levels of control the majority are larger.

Table 8-17 depicts the length of control periods for affected new landfills. Again, the landfills must operate the emissions controls for as long as their emissions exceed the selected cutoff level. The year when controls must begin varies from landfill to landfill; the length of time during which controls must be operated also varies from landfill to landfill, and so, therefore, does the date when controls may be removed. While some landfills must keep controls in place for as long as 124 years,

TABLE 8-16. SUMMARY INFORMATION FOR AFFECTED NEW LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
Number of affected landfills (Percent of total new landfills)	**247** (26)	**104** (11)	**41** (4)
Distribution of affected landfills by design capacity (10^6 Mg)			
≤ 1	**58** (23)	**0** (0)	**0** (0)
1 to 5	**121** (49)	**46** (44)	**10** (24)
5 to 10	**29** (12)	**22** (21)	**14** (34)
> 10	**39** (16)	**36** (35)	**17** (41)
Total	**247** (100)	**104** (100)	**41** (100)
Privately owned affected landfills (Percent of affected landfills)	**51** (21)	**24** (23)	**14** (35)

Note: The numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE 8-17. LENGTH OF CONTROL PERIOD FOR AFFECTED NEW LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
Average length of control period (years)	74.4	59.6	59.1
Distribution of affected landfills by length of control period (years)			
≤ 25	31 (13)	17 (16)	9 (22)
26 to 50	63 (26)	41 (39)	10 (24)
51 to 100	61 (25)	22 (21)	17 (41)
101 to 150	92 (37)	24 (23)	5 (12)
Total	247 (100.0)	104 (100.0)	41 (100.0)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE 8-18. LENGTH OF CONTROL PERIOD PRIOR TO CLOSURE FOR AFFECTED NEW LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
Average length of control period prior to closure (years)	**14.3**	**13.3**	**13.3**
Distribution of affected landfills by length of control period prior to closure (years)			
≤ 5	**36** (14)	**17** (16)	**7** (17)
6 to 10	**32** (13)	**5** (5)	**10** (24)
11 to 20	**152** (62)	**75** (72)	**17** (42)
21 to 50	**27** (11)	**7** (7)	**7** (17)
Total	**247** (100)	**104** (100)	**41** (100)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding.

the average length of control period is about 60 years for the 250 Mg and 100 Mg stringency levels, and 74 years for the 25 Mg stringency level. Table 8-17 also shows that the more stringent the level of control, the higher the proportion of landfills that will incur long periods of control.

Table 8-18 shows the average length of control period prior to closure for affected new landfills, and a frequency distribution of affected landfills by length of control prior to closure. In general, most affected new landfills need not begin controlling emissions until fairly close to their closure date. The average length of time between beginning controls and closure is 13 or 14 years. At the 25 Mg stringency level, 14% of affected landfills will have only 5 years or less of controls before closure, while 16% will have 5 years or less at the 100 Mg stringency level. Finally, 17% will have 5 years or less at the 250 Mg level.

Table 8-19 provides another measure of the severity of impacts on landfill owners from the regulatory alternatives under consideration. It describes the net present value of enterprise costs for affected new landfills. As discussed above, the streams of capital and operating costs incurred by the landfill owners over time are discounted to their present value in order to compare one landfill's costs to another's. To reflect the differences in the cost of capital for private and public landfill owners, different discount rates are used in the discounting process: costs for publicly owned landfills are discounted using a 4% rate, while the costs for privately owned landfills are discounted using an 8% rate. The net present value of capital costs and the net present value of operating costs are summed for each landfill, which yields the total net present value of enterprise costs. These costs are summed across landfills to estimate the aggregate (nationwide) net present value of enterprise costs.

Table 8-19 shows that the 247 new landfills affected by the 25 Mg level of control have total enterprise costs of $641 million, while the 104 new landfills affected by the 100 Mg level of stringency have an aggregate net present value of enterprise costs of $407 million, and the 41 new landfills affected by the 250 Mg stringency level have aggregate net present value of enterprise costs of $249 million. Although some landfills have a NPV of enterprise costs as high as $22 million at each stringency level, the average NPV enterprise costs per landfill are much lower. While the

TABLE 8-19. NET PRESENT VALUE OF ENTERPRISE COSTS FOR AFFECTED NEW LANDFILLS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National enterprise costs (10^6)			
Capital	**245**	**177**	**117**
Operating	**396**	**230**	**132**
Total	**641**	**407**	**249**
Average total enterprise cost per affected landfill (10^6)	**2.60**	**3.92**	**6.07**
Distribution of affected landfills by net present value of enterprise costs (10^6)			
≤ 0.5	**39** (16)	**7** (7)	**2** (5)
0.5 to 1.0	**41** (17)	**10** (10)	**2** (5)
1.0 to 3.0	**111** (45)	**53** (51)	**23** (56)
3.0 to 5.0	**36** (14)	**14** (13)	**2** (5)
>5.0	**20** (8)	**20** (19)	**12** (29)
Total	**247** (100)	**104** (100)	**41** (100)

Note: Numbers in parentheses are percentages. Net present value of enterprise costs is calculated using a 4 percent discount rate for publicly owned landfills and an 8 percent discount rate for privately owned landfills. Details may not add to totals due to rounding.

aggregate NPV enterprise costs are highest at the 25 Mg stringency level, the average NPV enterprise cost per facility for this level, $2.60 million, is lower than for the other two stringency levels, because so many more landfills with lower costs are affected by the 25 Mg stringency level. At the 100 Mg stringency level, the average NPV enterprise cost per facility is $3.92 million, while the average NPV enterprise cost per facility is $6.07 million at the 250 Mg stringency level.

The frequency distribution of affected new landfills by NPV of enterprise costs in Table 8-19 indicates that a higher proportion of affected landfills under the more stringent control alternatives experience a relatively low NPV of enterprise costs. For example, under the 25 Mg stringency level, one-third of affected facilities have a NPV of enterprise costs of $1 million or less. Under the 100 Mg stringency level, one-sixth have a NPV of enterprise costs of $1 million or less, and only 10% have a NPV of enterprise costs of $1 million or less under the 250 Mg stringency level.

Annualizing enterprise costs is another way of using these costs to assess impacts on landfill owners. The NPVs of enterprise costs for publicly owned landfills are annualized using a 4% rate of interest over the period of time during which the controls will be in place. For privately owned landfills, we annualize enterprise costs using an 8% rate of interest during the active operating life of the landfill, since privately owned landfills will not be able to recapture the costs of compliance after they close. We then divide these annualized enterprise costs by the reported quantity of waste that the landfills accepted in 1986.

The first line in Table 8-20 shows the national annualized enterprise cost per Mg of MSW accepted by affected new landfills for each stringency level. This is computed by summing the annualized enterprise cost for all affected landfills at a stringency level, and then dividing by the total MSW accepted by all those landfills. The national annualized cost per Mg of MSW accepted is less than $1.00 per Mg for all stringency levels. At the 250 Mg stringency level, the national cost is $0.46 per Mg. As the stringency increases to the 100 Mg level, the national annualized cost increases to $0.48 per Mg of MSW. At the most stringent 25 Mg cutoff level, the national annualized cost rises to $0.60 per Mg of MSW accepted.

TABLE 8-20. ANNUALIZED ENTERPRISE CONTROL COST PER Mg OF MSW FOR AFFECTED NEW LANDFILLS

	Stringency Level (Mg NMOC/yr)		
	25	**100**	**250**
National annualized cost per Mg MSW ($/Mg MSW)	**0.60**	**0.48**	**0.46**
Distribution of affected landfills by annualized cost per Mg MSW ($/Mg MSW)			
≤ 0.25	**10** (4)	**12** (12)	**5** (12)
0.25 to 0.50	**41** (17)	**31** (30)	**14** (34)
0.50 to 1.00	**77** (31)	**24** (23)	**12** (29)
1.00 to 3.00	**75** (30)	**37** (36)	**10** (24)
> 3.00	**44** (18)	**0** (0)	**0** (0)
Total	**247** (100)	**104** (100)	**41** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent over the life of the landfill. Details may not add to totals due to rounding.

Table 8-20 also has a frequency distribution of affected landfills by the annualized enterprise cost per Mg of MSW accepted. This distribution reveals that, the higher the stringency level, the higher the proportion of affected landfills incurring annualized costs greater than $1.00 per Mg of MSW accepted. At the least stringent 250 Mg cutoff level, only one-quarter of the 41 affected landfills have costs of $1.00 per Mg or higher, and no affected landfill experiences annualized costs exceeding $1.15 per Mg. At the 100 Mg stringency level, however, over one-third of the 104 affected landfills have annualized costs at least as high as $1.00 per Mg; at this stringency level, the maximum annualized cost is $1.89 per Mg of MSW. Finally, at the most stringent 25 Mg level, almost half of the 247 affected landfills have annualized costs of $1.00 per Mg or higher, and at least two landfills have annualized costs of $5.88 per Mg.

Table 8-21 assesses the potential impact of the regulatory alternatives on the households that will be served by these new landfills based on the annualized enterprise cost per household. We compute the overall annualized enterprise cost per household by summing the annualized enterprise costs for each affected landfill under each stringency level, and then we divide the summed annualized enterprise costs by the estimated number of households served by the affected landfills. The national cost per household varies from $2.69 at the 250 Mg stringency level to $2.78 at the 100 Mg stringency level to $3.48 at the 25 Mg stringency level.

As we found for closed/existing landfills, the 25 Mg stringency level has the highest proportion of affected new landfills incurring relatively high costs per household. At that stringency level, over three-fourths of the 247 affected landfills incur costs of $3.00 per household or more. At the 250 Mg stringency level, the proportion of landfills incurring costs of more than $3.00 per household falls to about one-half. At the 100 Mg stringency level, the proportion of affected landfills incurring costs per household as high as $3.00 is lowest of all—only 7% of the 104 affected landfills have costs that high.

Another way of assessing the possible impact of the regulatory alternatives under consideration is to examine the net present value (NPV) of social costs resulting from each possible stringency level (see Table 8-22). As with the NPV of enterprise costs, the aggregate total NPV of

TABLE 8-21. ANNUALIZED ENTERPRISE CONTROL COST PER HOUSEHOLD FOR AFFECTED NEW LANDFILLS

	Stringency Level (Mg NMOC/yr)		
	25	**100**	**250**
National annualized cost per household ($/Household)	**3.48**	**2.78**	**2.69**
Distribution of affected landfills by annualized cost per household ($/Household)			
≤ 0.75	**2** (1)	**15** (14)	**0** (0)
0.75 to 1.50	**7** (3)	**29** (28)	**7** (17)
1.50 to 3.00	**44** (18)	**53** (51)	**12** (29)
3.00 to 10.00	**121** (49)	**7** (7)	**22** (54)
> 10.00	**73** (30)	**0** (0)	**0** (0)
Total	**247** (100)	**104** (100)	**41** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent over the life of the landfill. Details may not add to totals due to rounding.

TABLE 8-22. NET PRESENT VALUE OF SOCIAL COSTS FOR AFFECTED NEW LANDFILLS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National social costs (10^6)			
Capital	788	548	362
Operating	614	348	200
Total	1,403	896	562
Average total social cost per affected landfill (10^6)	5.68	8.63	13.7
Distribution of affected landfills by net present value of social costs (10^6)			
≤ 0.5	7	0	0
	(3)	(0)	(0)
0.5 to 1.0	17	0	0
	(7)	(0)	(0)
1.0 to 3.0	92	39	7
	(37)	(37)	(17)
3.0 to 5.0	44	7	7
	(18)	(7)	(17)
5.0 to 10.0	65	36	15
	(26)	(35)	(37)
> 10.0	22	22	12
	(9)	(21)	(29)
Total	247	104	41
	(100.0)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of social cost is computed using a two-step discounting procedure. First, capital costs are annualized at 10 percent over the control period. Then, present values are computed by discounting annual operating costs and annualized capital costs at 3 percent. Details may not add to totals due to rounding

social costs increases as the level of stringency increases. At the most stringent 25 Mg cutoff level, the aggregate total NPV of social costs, $1.4 billion, is more than twice the aggregate total NPV of social costs at the 250 Mg level, $562 million. The aggregate total NPV of social costs at the 100 Mg level, $896 million, lies between the cost of the other stringency levels. Also following the pattern demonstrated by the enterprise costs, the number of affected landfills increases substantially as the stringency level increases, and the average NPV of social costs per landfill decreases as the level of stringency increases. While some landfills have NPV of social costs as high as $51 million, the average NPV of social costs per affected landfill ranges from $13.7 million at the 250 Mg stringency level, to $8.63 million at the 100 Mg stringency level, to $5.68 million at the 25 Mg stringency level. Finally, the frequency distribution in Table 8-22 shows, in a different manner than the averages, that the smaller number of affected landfills at the lower stringency levels have a higher NPV of social costs per landfill.

Our last measure of the cost to society of the §111(b) regulatory alternatives under consideration is the annualized net present value of social costs. As explained above, we annualized the net present value of the social cost for each affected landfill over the years from 1992 to the end of the landfill's control period using a 3% discount rate, and then we summed these individual annualized values to get the total annualized social cost. The resulting total annualized social cost for affected new landfills for each stringency level is:

- $45 million for the 25 Mg stringency level
- $30 million for the 100 Mg stringency level
- $19 million for the 250 Mg stringency level.

As expected, the least stringent regulatory alternative (the 250 Mg stringency level) has the lowest annualized social cost, while the most stringent regulatory alternative (the 25 Mg stringency level) has the highest annualized social cost.

Up to this point, we have assumed that the §111(b) regulatory alternatives under consideration will not affect the quantity of MSW going to new landfills. Actually, landfill emissions controls will increase the cost of landfilling relative to other MSW disposal options (i.e., incineration),

which will provide an incentive for some substitution among disposal technologies. In other words, increases in landfill costs attributable to §111(b) controls will cause a shift in MSW flows away from landfills and towards MWCs. However, EPA is also considering other regulations affecting both landfills and MWCs, as explained in Section 8.2. The net effect of all these regulations on MSW flows is not clear.

To help determine the possible effects on MSW flows of various EPA regulations under consideration, developed an econometric model of the actual choices made by communities between 1980 and 1986 with respect to building either a new landfill or a new MWC.[141] This model estimates the share of MSW going to landfills and MWCs based on disposal costs and the socioeconomic characteristics of communities. By adding the estimated control costs associated with various landfill and MWC regulations to landfill and MWC disposal costs, respectively, the model predicts changes in MSW flows attributable to the regulations.

Table 8-23 presents the results of applying the Bentley/Spitz model incrementally to three EPA regulations: the Subtitle D controls under the Resource Conservation and Recovery Act, the CAA §111(b) controls applying to MWCs, and the CAA §111(b) controls applying to landfills. Under baseline conditions, about 72% of MSW goes to landfills. In other words, the choices that communities make regarding building new MWCs and landfills result in 72% of their MSW going to landfills and 28% going to MWCs in the absence of any new EPA regulations. The Subtitle D controls will increase the cost of landfilling, which will cause more communities to choose the MWC disposal technology. However, the CAA §111(b) controls under consideration for MWCs will substantially increase the costs of this disposal technology, which will result in a large shift in MSW flows towards landfills according to the Bentley/Spitz model. Finally, the CAA §111(b) controls under consideration for landfills will increase landfilling disposal costs slightly, so these controls will only result in a very small shift in MSW flows towards MWCs.*

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*As indicated in Table 8-20, the annualized enterprise control cost per Mg of MSW for affected new landfills is $0.48 under the 100 Mg stringency level. In contrast, the annualized enterprise control cost per Mg of MSW for affected new MWCs is $9.65 for Regulatory Alternative IV under Scenario III.[142] This supports the conclusion that the impact of the landfill emissions controls on MSW flows will be much smaller than the impact of the MWC emissions controls.

TABLE 8-23. MSW TONNAGE SHARES OF MUNICIPAL WASTE COMBUSTORS (MWCS) AND LANDFILLS WITHOUT AND WITH VARIOUS EPA REGULATIONS

	MSW Tonnage Shares		
	MWCs	Landfills	Total
Baseline	27.75%	72.25%	100%
Baseline Plus Subtitle D Control Costs*	30.66%	69.34%	100%
Baseline Plus Subtitle D and MWC Emissions Control Costs**	21.24%	78.55%	100%
Baseline Plus Subtitle D, MWC and Landfills Emissions Control Costs***	21.61%	78.39%	100%

*Estimates of Subtitle D Control costs taken from the RIA[143].

**Estimates of MWC emissions control costs are based on Regulatory Alternative IV under Scenario III[144].

***Landfills emissions control costs are based on the 100 Mg stringency level.

Overall, the three regulations will increase MSW flows to landfills about 6 percentage points (i.e., from 72% to 78%). These results suggest that some increase in MSW acceptance rates at new landfills is appropriate for estimating the costs of the §111(b) regulatory alternatives under consideration for landfills. However, the three assumptions (discussed in Section 8.3) producing high MSW acceptance rates in the costing model in Chapter 7 probably still lead to overestimates of the costs of these regulatory alternatives.

8.4.2.2 Energy Recovery Option. Under the energy recovery option, the landfill owners are allowed to either combust their emissions or control them as part of energy recovery, depending upon which approach is least costly for them. Undoubtedly, some landfills will find energy recovery not only less costly than flares, but actually profitable. We assume that the owners of such landfills would install energy recovery systems even in the absence of the emissions control regulation. Therefore, we do not attribute either the emissions reductions or the costs of these energy recovery systems to the regulatory alternatives under consideration. We limit our analysis, therefore, to those landfills for which the costs of installing and operating emissions controls of either type will be positive. Appendix F has the tables on the affected new landfills having positive energy recovery costs.

By eliminating landfills that profit from energy recovery, the §111(b) regulatory alternatives affect far fewer new landfills. Table F-8 shows that the number of affected new landfills varies from 10 under the least stringent 250 Mg level of control, to 39 under the 100 Mg stringency level, and 140 under the 25 Mg stringency level. Additionally, the frequency distribution of affected new landfills by design capacity reveals that no small landfills (1 million Mg or less) are affected by the 100 Mg and 250 Mg stringency levels under the energy control option. As discussed above, privately owned landfills may have less flexibility in paying for emissions controls, because they must recapture the costs of these controls through increased user fees while the landfill is still accepting MSW. Under the 250 Mg and 100 Mg stringency levels, none of the affected landfills are privately owned. Under the 25 Mg stringency level, however, there are 34 privately owned landfills, which is almost one-quarter of the affected new landfills.

Table F-9 shows the length of the control period for affected new landfills with positive energy recovery costs. The average length of the control period ranges from 56 years for the 100 Mg stringency level to 75 years for the 250 Mg stringency level. The average length of the control period for the 25 Mg and 100 Mg stringency levels is slightly below the average length of the control period for these stringency levels under the flare option (see Table 8-17). However, the average length of the control period under the 250 Mg stringency level increases under the energy recovery option, despite no affected landfills having a control period in excess of 100 years at this stringency level.

Another measure of the potential impacts from the regulatory alternatives is the length of time after controls begin and before closure of the landfill. If the landfill is still accepting MSW, its owners can attempt to increase user fees to recapture some of the costs of compliance. Table F-10 shows the length of control period prior to closure. While there are many fewer affected landfills when landfills that profit from energy recovery are eliminated, the length of control period prior to closure is slightly shorter for the landfills with positive energy recovery costs. Comparing Table F-10 with Table 8-18 reveals that the landfills with positive energy recovery costs have shorter periods of time prior to closure when compared with all affected new landfills under the flare option. Both the average length of control period prior to closure and the distribution of affected landfills by length of control period prior to closure at all three stringency levels demonstrate the difference. Under the flare option, between 14% and 17% of affected new landfills close within five years of implementing emissions controls; alternatively, between 18% and 30% of affected new landfills with positive energy recovery costs close within five years of implementing emissions controls.

To assess the impact of the regulatory alternatives on the owners of affected new landfills under the energy recovery option, we compute the net present value (NPV) of enterprise costs under the flare option and the energy recovery option, omitting landfills that would profit from energy recovery. Then, we assume that the landfill owner will choose the least costly of the control options. To compute the national values at the top of Table F-11, we aggregate the NPV of capital and operating costs for

affected landfills for each stringency level. Then we sum the energy recovery revenues for the landfills that select the energy recovery option for each stringency level. Finally, we calculate the total aggregate NPV of enterprise costs by adding the capital and operating sums and subtracting the revenue sum. At the 250 Mg stringency level, this total equals about $18 million, or an average of $1.83 million for each of the affected new landfills. At the 100 Mg stringency level, the total aggregate NPV of enterprise costs is $63 million, or an average of $1.61 million for each of the affected landfills at that level. Finally, at the 25 Mg stringency level, the total NPV of enterprise costs is $150 million, which averages $1.07 million for each of the affected landfills.

Table F-11 has a frequency distribution of affected new landfills by NPV of enterprise costs. At the 250 Mg stringency level, all the affected landfills experience NPV of enterprise costs between $500,000 and $2.2 million. At the 100 Mg stringency level, all the affected landfills have NPV of enterprise costs between $500,000 and $3.5 million. Finally, NPV of enterprise costs range from below $500,000 to $3.8 million at the 25 Mg stringency level.

Another measure of the impacts of the regulatory alternatives on landfills is the annualized enterprise control cost per Mg of MSW accepted by the landfill. Table F-12 shows the annualized enterprise costs for landfills with positive energy recovery costs when owners are allowed to select the least costly means of achieving emission reductions, either using flares or using energy recovery. At each stringency level, the annualized cost per Mg of MSW is less than $1.00. At the 250 Mg stringency level the overall annualized cost is only $0.59 per Mg. It is $0.92 per Mg at the 100 Mg stringency level, and it is $0.95 per Mg at the 25 Mg stringency level. These national annualized costs per Mg of MSW are between 28% and 92% higher than the national annualized costs per Mg of MSW under the flare option, because many of the low cost per Mg landfills under the flare option are omitted from the affected landfills under the assumptions of the energy recovery option.

The frequency distribution of affected new landfills by annualized enterprise control costs per Mg of MSW in Table F-12 shows that all the affected landfills have annualized costs between $0.50 and $3.00 per Mg for

the 100 Mg and 250 Mg stringency levels. The maximum annualized cost at the 250 Mg stringency level is $1.08 per Mg, and the maximum at the 100 Mg stringency level is $1.42 per Mg. At the 25 Mg stringency level, on the other hand, affected landfills have unit costs ranging from below $0.25 per Mg to $5.30 per Mg. Over one-quarter of the affected landfills under this stringency level have annualized costs per Mg of $3.00 or higher.

To assess the possible impacts of the emissions control alternatives on the households served by affected landfills, we computed the annualized enterprise control costs per household. Table F-13 has these costs for affected landfills with positive energy recovery costs when landfill owners may choose either the flare option or the energy recovery option. At the 250 Mg stringency level, the national annualized cost is $3.41 per household. The annualized cost per household increases to $5.36 at the 100 Mg stringency level, and the annualized cost per household is $5.53 at the 25 Mg stringency level. As was the case for annualized costs per Mg of MSW, national annualized household costs under the energy recovery option are higher than annualized household costs under the flare option for reasons discussed above.

Table F-13 also contains a frequency distribution of affected new landfills by the annualized cost per household. At the 250 Mg stringency level, the 10 affected landfills have annualized costs between $1.50 and $10.00 per household. At the 100 Mg stringency level, the 39 affected landfills have annualized enterprise costs between $3.00 and $10.00 per household. Finally, the 140 affected landfills at the 25 Mg stringency level have annualized enterprise costs ranging from less than $0.75 per household to more than $10.00 per household.

Table F-14 shows another means of measuring the cost of complying with the emissions control regulations under the energy recovery option--the NPV of social costs. The aggregate NPV of social costs falls almost 78% at the 25 Mg stringency level under the energy recovery control option. At the 100 Mg stringency level, the aggregate NPV of social costs falls by 84% under this option, and the aggregate NPV of social costs falls by about 90% at the 250 Mg stringency level compared to the costs under the flare option. This decrease in the aggregate NPV of social costs is largely the result of a reduction in the number of affected landfills. However, the

average total social cost per affected landfill under the energy recovery option is less than half the average total social cost per affected landfill under the flare option for all three stringency levels.

To provide another perspective on the social cost of the §111(b) regulatory alternatives under consideration, we calculated the annualized social cost for the three stringency levels under the energy recovery option. These costs for the affected new landfills under the energy recovery option are:

- $10.5 million for the 25 Mg stringency level
- $4.3 million for the 100 Mg stringency level
- $1.6 million for the 250 Mg stringency level.

These annualized social costs are substantially lower than the annualized social costs under the flare option. For example, the $4.3 million annualized social cost for the 100 Mg stringency level under the energy recovery option is just one-seventh of the $30.2 million annualized social cost for the same stringency level under the flare option.

8.5 ANALYSIS OF EMISSIONS REDUCTIONS AND COST-EFFECTIVENESS

At the same time that we are considering the costs of complying with the §111(d) and 111(b) regulatory alternatives under consideration, we must also consider the cost-effectiveness of these alternatives. In this case cost-effectiveness is measured as the annualized compliance cost per Mg of reduction in the emission of nonmethane organic compounds (NMOCs). We discuss compliance costs for each stringency level and each option in the previous section. In this section, we examine both the emissions reductions and cost-effectiveness of the regulatory alternatives under consideration for both closed/existing and new landfills under each of two control options. We will first examine the emissions reductions and the cost-effectiveness of the flare control option for closed and existing landfills. Then we present the same two measures for these landfills under the energy recovery option. Finally, we examine the emissions reductions and cost-effectiveness of both control options for new landfills.

8.5.1 Section 111(d) Guidelines

As shown in Table 8-6 in Section 8.4, the number of closed and existing landfills affected by the §111(d) Guidelines under the flare control

option ranges from 386 at the 250 Mg stringency level to 853 at the 100 Mg level to 1884 at the 25 Mg stringency level. As explained above, we omit landfills that make a profit from energy recovery when analyzing the impacts of the energy recovery option. So the number of closed and existing landfills affected by the guidelines under the energy recovery option is lower: 77 under the 250 Mg stringency level, 325 under the 100 Mg level, and 1024 under the 25 Mg level.

8.5.1.1 Flare Option. Table 8-24 shows the emissions reductions resulting from the three regulatory alternatives under the flare option. Total undiscounted NMOC emissions reductions range from 24.1 million Mg at the 250 Mg stringency level, to 28.6 million Mg at the 100 Mg stringency level, to 33.2 million Mg at the 25 Mg stringency level. These emissions reductions are spread over the period of time during which the affected landfills are using the flare emission controls. In order to compare emissions reductions with the costs from Section 8.4, we discount the NMOC emissions reductions using a 3% rate of discount. The discounted NMOC emissions reductions range from 9.6 million Mg at the 250 Mg stringency level to 11.2 million Mg at the 100 Mg stringency level to 12.6 million Mg at the 25 Mg stringency level. The average discounted NMOC emission reduction decreases as the stringency level increases, because the number of affected landfills increases faster than the NMOC emissions reductions. Thus, the average NMOC emission reduction per affected landfill is 24,966 Mg at the 250 Mg stringency level, 13,110 Mg at the 100 Mg stringency level, and 6,674 Mg at the 25 Mg stringency level.

We combined these measures of NMOC emissions reductions with the discounted NPV of social costs presented in Table 8-15 to estimate the cost-effectiveness of the flare option for closed and existing landfills (see Table 8-25). At the top of the table is the national cost-effectiveness of each stringency level, computed by dividing the aggregate NPV of total social cost by the total discounted NMOC emissions reduction. The national cost-effectiveness of the flare option at the 250 Mg stringency level is $407 per Mg of NMOC reduced. At the 100 Mg stringency level, the national cost-effectiveness is $640 per Mg of NMOC reduced, and the national cost-effectiveness is $927 per Mg of NMOC reduced at the most stringent 25 Mg level.

TABLE 8-24. NET PRESENT VALUE OF EMISSIONS REDUCTIONS FOR AFFECTED CLOSED AND EXISTING LANDFILLS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
Undiscounted NMOC emission reduction (10^6 Mg)	33.2	28.6	24.1
Discounted NMOC emission reduction (10^6 Mg)	12.6	11.2	9.64
Average discounted NMOC emission reduction per affected landfill (Mg)	6,674	13,110	24,966
Distribution of affected landfills by discounted NMOC emission reduction per affected landfill (Mg)			
≤ 1,000	593 (31)	104 (12)	22 (6)
1,000 to 2,000	453 (24)	138 (16)	17 (4)
2,000 to 5,000	425 (23)	228 (27)	43 (11)
5,000 to 10,000	162 (9)	135 (16)	63 (16)
> 10,000	251 (13)	248 (29)	241 (63)
Total	1,884 (100)	853 (100)	386 (100)

Note: Numbers in parentheses are percentages. Net present value of emission reductions is calculated using a 3 percent discount rate. Details may not add to totals due to rounding.

TABLE 8-25. COST EFFECTIVENESS FOR AFFECTED CLOSED AND EXISTING LANDFILLS

	Stringency Level (Mg NMOC/yr)		
	25	100	250
National cost effectiveness ($/Mg NMOC)	927	640	407
Distribution of affected landfills by cost effectiveness ($/Mg NMOC)			
≤ 1,000	382	433	295
	(20)	(51)	(76)
1,000 to 2,000	447	251	70
	(24)	(30)	(18)
2,000 to 5,000	721	123	19
	(38)	(14)	(5)
5,000 to 10,000	269	24	2
	(14)	(3)	(1)
> 10,000	65	22	0
	(4)	(2)	(0)
Total	1,884	853	386
	(100)	(100)	(100)
Incremental cost effectiveness	3,225	2,097	—

Note: Numbers in parentheses are percentages. Cost effectiveness is calculated by dividing the net present value of social cost by the discounted NMOC emission reduction (see Tables 8-15 and 8-24). Details may not add to totals due to rounding.

The frequency distribution of affected landfills by cost-effectiveness demonstrates that as the stringency level decreases, an increasing proportion of landfills has a cost-effectiveness under $1,000 per Mg of NMOC reduced. At the 25 Mg stringency level, only 20% of affected landfills have cost-effectiveness measures that low, while more than half of the affected landfills fall below $1,000 per Mg of NMOC at the 100 Mg stringency level. Finally, three-fourths of the affected landfills have a cost-effectiveness less than $1,000 per Mg of NMOC at the 250 Mg stringency level. At the bottom of the table, incremental cost-effectiveness measures the change in national cost-effectiveness experienced as the stringency level increases first from 250 Mg to 100 Mg, and then from 100 Mg to 25 Mg. As the stringency level increases from 250 Mg to 100 Mg, the incremental cost-effectiveness is $2,097 per Mg of NMOC reduced. Moving from 100 Mg to 25 Mg results in an incremental cost effectiveness of $3,225 per Mg of NMOC reduced.

8.5.1.2 Energy Recovery Option. Table F-15 presents the emissions reductions resulting from the three regulatory alternatives under the energy recovery option. Because so many landfills would find energy recovery profitable, there are far fewer affected landfills under the energy recovery option. Consequently, the total undiscounted NMOC emissions reductions under this option are much less than under the flare option. Specifically, total undiscounted NMOC emissions reductions range from 1.26 million Mg at the 250 Mg stringency level, to 3.06 million Mg at the 100 Mg stringency level, to 5.81 million at the 25 Mg stringency level. These emissions reductions are spread over the period of time during which landfills are operating the emission controls. In order to compare emissions reductions with the costs from Section 8.4, we discount the NMOC emissions reductions using a 3% rate of discount. The discounted NMOC emissions reductions range from 0.59 million Mg at the 250 Mg stringency level to 1.15 million Mg at the 100 Mg stringency level to 2.04 million Mg at the 25 Mg stringency level. The average discounted NMOC emission reduction decreases as the stringency level increases, because the number of affected landfills increases faster than the NMOC emissions reductions. Thus, the average NMOC emission reduction per affected landfill is 7,560 Mg at the 250 Mg stringency level, 3,546 Mg at the 100 Mg stringency level, and 1,993

Mg at the 25 Mg stringency level. The averages are less than one-third of the average NMOC emission reductions under the flare option.

Table F-16 shows the social cost-effectiveness of the energy recovery option. The national cost-effectiveness measures are higher at each level of stringency than the cost-effectiveness of the stringency levels under the flare option, with the greatest increase occurring at the 25 Mg stringency level. The frequency distribution of affected landfills by cost-effectiveness under the energy recovery option shows that the affected landfills are concentrated in the lower cost-effectiveness categories at the less stringent levels of control. As under the flare option, the degree of concentration increases as the level of stringency decreases. At the 25 Mg stringency level, only 15% of affected landfills have a cost-effectiveness under $1,000 per Mg of NMOC reduced. At the 100 Mg level, 58% fall below $1,000 per Mg of NMOC, and 88% fall below $1,000 per Mg of NMOC at the 250 Mg level. Also displaying a similar pattern to the flare option, the incremental cost-effectiveness increases as the level of stringency increases, although the measures of incremental cost-effectiveness are much lower at each level of stringency than under the flare option.

8.5.2 Section 111(b) Standards

New landfills will be regulated under the §111(b) Standards. We present measures of emissions reductions and cost-effectiveness for affected new landfills under each control option in this section.

8.5.2.1 Flare Option. Under the flare control option, the number of affected new landfills ranges from 41 at the 250 Mg stringency level, to 104 at the 100 Mg stringency level, to 247 at the 25 Mg stringency level. Table 8-26 shows the emissions reductions for new landfills under this control option. The first line shows the total undiscounted NMOC emissions reductions at each stringency level. These measures, showing the total emissions reductions achieved throughout the control period for all affected new landfills, ranges from 1.74 million Mg at the 250 Mg stringency level, to 2.33 million Mg at the 100 Mg stringency level, to 2.93 million Mg at the 25 Mg stringency level.

In order to compare emissions reductions between landfills when the emissions reductions occur at different times at different landfills, we

TABLE 8-26. NET PRESENT VALUE OF EMISSIONS REDUCTIONS FOR AFFECTED NEW LANDFILLS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
Undiscounted NMOC emission reduction (10^6 Mg)	2.93	2.33	1.74
Discounted NMOC emission reduction (10^6 Mg)	0.99	0.83	0.63
Average discounted NMOC emission reduction per affected landfill (Mg)	4,015	7,983	15,278
Distribution of affected landfills by discounted NMOC emission reduction per affected landfill (Mg)			
≤ 1,000	106 (43)	2 (2)	5 (12)
1,000 to 2,000	39 (16)	15 (14)	2 (5)
2,000 to 5,000	68 (27)	53 (51)	2 (5)
5,000 to 10,000	10 (4)	10 (10)	8 (19)
> 10,000	24 (10)	24 (23)	24 (59)
Total	247 (100)	104 (100)	41 (100)

Note: Numbers in parentheses are percentages. Net present value of emission reductions is calculated using a 3 percent discount rate. Details may not add to totals due to rounding.

discount the NMOC emissions reductions using a 3% rate of discount. This discounted NMOC emission reduction, when summed across all affected landfills, ranges from 0.63 million Mg at the 250 Mg stringency level to 0.83 million Mg at the 100 Mg stringency level and 0.99 million Mg at the 25 Mg stringency level.

The average discounted NMOC emission reduction per affected landfill is much higher at the 250 Mg stringency level than at the 25 Mg stringency level because the number of affected landfills falls faster than discounted NMOC reduction as the stringency level decreases. At the 250 Mg stringency level, the average discounted NMOC emission reduction is 15,278 Mg of NMOC, more than three times the average discounted NMOC emission reduction per landfill at the 25 Mg stringency level (4,015 Mg of NMOC). At the 100 Mg stringency level, the average discounted NMOC emission reduction, 7,983 Mg of NMOC per affected landfill, falls between the average emission reduction values of the other two stringency levels. The frequency distribution of affected new landfills by discounted NMOC emission reduction shows that the proportion of landfills achieving relatively greater NMOC emissions reductions increases as the stringency level decreases.

We can construct cost-effectiveness measures for affected new landfills by combining information about emission reduction with information about the NPV of social costs in Table 8-22. Specifically, we estimate national cost-effectiveness by dividing the total social cost by the total discounted emission reduction for each stringency stringency level. As shown in Table 8-27 this value ranges from $897 per Mg of NMOC reduced at the 250 Mg stringency level, to $1,081 per Mg of NMOC at the 100 Mg level, to $1,416 per Mg of NMOC at the 25 Mg stringency level. The frequency distribution demonstrates that, as with closed/existing landfills, the proportion of affected new landfills having cost-effectiveness measures less than $1000 per Mg of NMOC increases as the degree of stringency decreases. At the 25 Mg stringency level, only 13% of landfills have a cost-effectiveness under $1,000 per Mg of NMOC, while at the 100 Mg stringency level, 44% have a cost-effectiveness of $1,000 per Mg or less. At the 250 Mg stringency level, 59% of affected landfills have a cost-effectiveness under $1,000 per Mg.

The last line of Table 8-27 shows incremental cost-effectiveness--i.e., the change in cost-effectiveness experienced as one moves from the 250 Mg stringency level to the 100 Mg level, and then from the 100 Mg stringency level to the 25 Mg stringency level. As the stringency level increases from 250 Mg to 100 Mg, the incremental cost-effectiveness is $1,648 per Mg of NMOC reduced. The incremental cost-effectiveness of moving from the 100 Mg stringency level to the 25 Mg stringency level is $3,136 per Mg of NMOC reduced.

8.5.2.2 Energy Recovery Option. Table F-17 presents the emissions reductions for affected new landfills with positive energy recovery costs. The undiscounted NMOC emission reduction for each stringency level ranges from 0.25 million Mg of NMOC reduced at the 250 Mg stringency level, to 0.49 million Mg of NMOC reduced at the 100 Mg stringency level, to 0.83 million Mg at the 25 Mg stringency level. The discounted NMOC emissions reductions range from 0.06 million Mg at the 250 Mg stringency level to 0.25 million Mg at the 25 Mg stringency level. As the level of stringency decreases, the average discounted NMOC emission reduction per affected new landfill increases, because the number of affected landfills falls more rapidly than the discounted NMOC emissions reductions. At the 25 Mg stringency level, the average discounted NMOC emission reduction per affected landfill is 1,765 Mg. At the 100 Mg stringency level, the average discounted emission reduction is 3,818 Mg per affected landfill, while the average discounted NMOC emission reduction per affected landfill rises to 6,680 Mg per affected landfill at the 250 Mg stringency level. Again, the smaller number of landfills affected at the 250 Mg stringency level experience greater emissions reductions on average. The frequency distribution of affected landfills by discounted NMOC emission reduction per affected landfill (at the bottom of Table F-17) supports this consideration.

Table F-18 shows the cost-effectiveness of the three stringency levels for the energy recovery control option for affected new landfills. The national cost-effectiveness of each stringency level varies from $891 per Mg of NMOC reduced at the 250 Mg stringency level to $963 per Mg of NMOC reduced at the 100 Mg level, to $1,244 per Mg of NMOC reduced at the 25 Mg stringency level. These national cost-effectiveness measures are lower than the cost-effectiveness of the stringency levels under the flare option.

TABLE 8-27. COST EFFECTIVENESS FOR AFFECTED NEW LANDFILLS

	Stringency Level (Mg NMOC/yr)		
	25	100	250
National cost effectiveness ($/Mg NMOC)	**1,416**	**1,081**	**897**
Distribution of affected landfills by cost effectiveness ($/Mg NMOC)			
≤ 1,000	**31** (13)	**46** (44)	**24** (59)
1,000 to 2,000	**68** (27)	**39** (38)	**7** (17)
2,000 to 5,000	**102** (41)	**19** (18)	**10** (24)
5,000 to 10,000	**39** (16)	**0** (0)	**0** (0)
> 10,000	**7** (3)	**0** (0)	**0** (0)
Total	**247** (100)	**104** (100)	**41** (100)
Incremental cost effectiveness	**3,136**	**1,648**	—

Note: Numbers in parentheses are percentages. Cost effectiveness is calculated by dividing the net present value of social cost by the discounted NMOC emission reduction (see Tables 8-22 and 8-26). Details may not add to totals due to rounding.

The frequency distribution in Table F-18 demonstrates that the proportion of affected landfills experiencing a cost-effectiveness of $1,000 per Mg of NMOC reduced or less, increases substantially as the level of stringency decreases. At the 25 Mg stringency level, only one-sixth of affected new landfills have a cost-effectiveness of $1,000 per Mg of NMOC or less, while 38% are below that level of cost-effectiveness at the 100 Mg stringency level. At the 250 Mg stringency level, 70% of the affected new landfills have a cost-effectiveness under $1,000 per Mg of NMOC reduced.

Finally, at the bottom of Table F-18, incremental cost-effectiveness is $870 per Mg of NMOC reduced as the stringency level increases from 250 Mg to 100 Mg. Moving from the 100 Mg stringency level to the 25 Mg stringency level results in an incremental cost-effectiveness of $1,661 per Mg of NMOC reduced. These incremental cost-effectiveness values are about one-half of the corresponding incremental cost-effectiveness values under the flare option.

8.6 ANALYSIS OF DISTRIBUTIONAL IMPACTS

The Regulatory Flexibility Act of 1980 requires federal agencies to determine if regulations will have a "significant economic impact on a substantial number of small entitities." According to EPA guidelines,[145] regulatory impacts are significant if:

- compliance costs are greater than five percent of production costs,
- compliance costs, as a percent of sales, are at least 10 percent higher for small entities than for other entities,
- capital costs of compliance are a significant portion of available capital, or
- the regulation is likely to result in closures of small entities.

The guidelines indicate that a "substantial number" of small entities is "more than 20 percent of these (small entities)." Finally, the EPA generally relies upon Small Business Administration guidelines for identifying "small entities."[146] However, the Regulatory Flexibility Act defines small government jurisdictions as those having fewer than 50,000 people. Since over three-fourths of U.S. landfills are owned by government

agencies, the potential impacts of the regulatory alternatives on small governmental entities are very relevant.

As explained below, the §111(d) Guidelines and 111(b) Standards under consideration will not affect a substantial number of small entities under EPA guidelines. Consequently, regulatory flexibility analyses are not required for these two rulemakings. Nevertheless, this section presents some distributional impacts on households and government jurisdictions of the flare option for the three stringency levels under consideration for the §111(d) Guidelines and 111(b) Standards. These distributional impacts rely on household and governmental data developed by EPA's Office of Solid Waste (OSW) for a landfills rulemaking under Subtitle D of the Resource Conservation and Recovery Act (RCRA).

8.6.1 Section 111(d) Guidelines

As indicated earlier in Table 8-6, the 25, 100, and 250 Mg stringency levels for the §111(d) Guidelines affect only 26%, 12%, and 5%, respectively, of all the closed and existing landfills in the United States in 1992. Since most landfills are small (i.e., 1 million Mg of design capacity or less), while the regulatory alternatives under consideration affect mainly large landfills (i.e., landfills with a design capacity over 1 million Mg), it is very unlikely that any of the stringency levels will affect more than 20 percent of the small landfills.*

To further investigate the impacts of the 25, 100, and 250 Mg stringency levels on small landfills, we analyzed the distribution of affected closed and existing landfills by design capacity relative to the total number of closed and existing landfills in the same size categories. All three stringency levels affect less than 10 percent of the closed and

* Lacking information on the size of governmental jurisdictions served by most landfills, we assume that small landfills serve small municipalities. This assumption is reasonable for two reasons. First, it is very unlikely that small municipalities will have large landfills, given the high cost of developing and operating large landfills. Second, large municipalities generate large amounts of solid waste, which requires a large amount of disposal capacity. Because of economies of scale in landfill operations and the difficulty of siting landfills, large municipalities will probably not be served by several small landfills. However, some large municipalities may be served by a municipal waste incinerator and a small landfill. In such cases, impacts on small landfills will not necessarily imply impacts on small municipalities.

existing landfills having a design capacity of 1 million Mg or less. While the 100 Mg stringency level affects 12% of the closed and existing landfills in total, it affects less than 4% of the closed and existing small landfills (i.e., landfills with 1 million Mg of design capacity or less). In conclusion, the §111(d) Guidelines do not require a Regulatory Flexibility Analysis, because they do not affect a significant number of small entities.

Although a Regulatory Flexibility Analysis is not required by the §111(d) Guidelines, we examine some distributional impacts of the various stringency levels under consideration. As indicated previously, these distributional impacts rely on household and governmental data developed by EPA's OSW for a landfills rulemaking under Subtitle D of RCRA. These data were available for only a subset of the affected closed and existing landfills for the three stringency levels under consideration for the §111(d) Guidelines.* The specific distributional impacts examined for the subset of affected landfills are:

- population of the service area
- annualized control costs per household
- annualized control costs as a percentage of annual local taxes paid by households
- net present value of capital costs as a percentage of net municipal debt (for publicly owned landfills).

The first measure (i.e., population of the service area) shows the number of people served by the affected landfills. This provides information on the size of the communities affected by the regulatory alternatives under consideration. The second measure reflects the potential annual cost of the controls to the households served by the affected landfills. The third

*The affected closed and existing landfills for which OSW data are available are generally smaller (in terms of design capacity, refuse in place in 1987, and the amount of MSW received in 1986) than the other affected landfills. In fact, the size difference is statistically significant for the affected landfills under the 25 Mg stringency level according to Student-t tests on design capacity and refuse in place. The size differences between the affected closed and existing landfills for which OSW data are available and the other affected landfills are not statistically significant under the 100 Mg and 250 Mg stringency levels.

measure examines the relative impact of the controls on households, by comparing annual control costs to households' annual local tax "burden." Finally, the fourth measure provides some information on the relative size of the capital costs of the regulatory alternatives under consideration for the affected municipalities.

Table 8-28 shows the population of the service area for the subset of affected closed and existing landfills. Approximately half of the affected landfills serve between 10,000 and 50,000 people under all three stringency levels. In general, as the stringency level increases, more landfills serving smaller communities are affected, as indicated by the changes in the distribution of affected landfills by the service area population. About one-fifth of the affected landfills at the 100 Mg stringency level serve 10,000 people or less, while another one-fifth serve 10,000 to 25,000 people.

The households served by more than two-thirds of the subset of affected closed and existing landfills incur less than $25 per year in control costs under all three stringency levels (see Table 8-29). The households served by 18% of the affected landfills incur more than $50 per year in control costs under the 100 Mg stringency level.* Nevertheless, the national average control cost per household is just $13 for the 100 Mg stringency level.

To further investigate the potential household impacts of the emissions controls under consideration, Table 8-30 shows annualized control costs as a percentage of local taxes paid by households in the service area of the subset of affected closed and existing landfills. The national average control cost as a percentage of local taxes paid by households is under 1.3% for all three stringency levels. Control costs as a percentage of local taxes paid are less than or equal to 1% for households served by 40% of the affected landfills at the 100 Mg stringency level. At the other

*The number of households in the service areas of these landfills is low compared to the amount of MSW going into the landfills. In other words, the amount of waste going into the landfills in these areas implies a greater number of households based on the typical amount of MSW generated by households. So the relatively high household costs for these affected landfills are a result of overestimated control costs stemming from overestimated MSW acceptance rates and/or underestimated numbers of households served by these landfills.

TABLE 8-28. SERVICE AREA POPULATION FOR A SUBSET OF THE AFFECTED CLOSED AND EXISTING LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
National average service area population (10^3 people)	79.5	138.9	107.2
Distribution of affected landfills by service area population (10^3 people)			
≤ 10	315 (28)	95 (21)	15 (8)
10 to 25	278 (25)	89 (19)	41 (23)
25 to 50	254 (23)	133 (28)	48 (27)
50 to 150	169 (15)	82 (17)	34 (19)
150 to 500	65 (6)	48 (10)	38 (21)
> 500	27 (2)	24 (5)	5 (3)
Total	1,108 (100)	471 (100)	181 (100)

Note: The numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE 8-29. ANNUALIZED ENTERPRISE COSTS PER HOUSEHOLD FOR A SUBSET OF THE AFFECTED CLOSED AND EXISTING LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
National average annualized cost per household ($/Household)	**9.49**	**12.91**	**9.46**
Distribution of affected landfills by annualized cost per household ($/Household)			
≤ 5	**217** (20)	**89** (19)	**56** (31)
5 to 10	**239** (22)	**131** (28)	**46** (26)
10 to 25	**303** (27)	**94** (20)	**41** (23)
25 to 50	**170** (15)	**72** (15)	**19** (10)
> 50	**179** (16)	**85** (18)	**19** (10)
Total	**1,108** (100)	**471** (100)	**181** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned closed and existing landfills are annualized at 4 percent over the control period. Costs for privately owned existing landfills are annualized at 8 percent from 1992 to the year of closure. Costs for privately owned closed landfills are annualized at 8 percent over the the control period. Costs for Details may not add to totals due to rounding.

TABLE 8-30. ANNUALIZED ENTERPRISE COST AS A PERCENTAGE OF LOCAL TAXES PAID BY HOUSEHOLDS IN THE SERVICE AREA FOR A SUBSET OF THE AFFECTED CLOSED AND EXISTING ~~AFFECTED~~ LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
National average annualized enterprise cost as a percent of taxes paid by households (%)	0.9	1.2	1.0
Distribution of affected landfills by average annualized cost as a percent of taxes paid by households (%)			
≤ 1	452 (41)	189 (40)	77 (43)
1 to 2.5	341 (31)	142 (30)	68 (38)
2.5 to 10	208 (19)	89 (19)	29 (16)
> 10	107 (10)	51 (11)	7 (4)
Total	1,108 (100)	471 (100)	181 (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned closed and existing landfills are annualized at 4 percent over the control period. Costs for privately owned existing landfills are annualized at 8 percent from 1992 to the year of closure. Costs for privately owned closed landfills are annualized at 8 percent over the the control period. Details may not add to totals due to rounding.

extreme, control costs exceed 10% of local taxes paid for households served by one-ninth of the affected landfills under this same stringency level.*

As a final measure of the distributional impact of the §111(d) regulatory alternatives under consideration, Table 8-31 examines the net present value of capital costs as a percentage of net municipal debt for a subset of affected publicly owned closed and existing landfills. Overall, the capital costs of the three stringency levels under consideration represent less than 2.5% of the net debt of municipalities served by publicly owned closed and existing landfills. Capital costs are less than or equal to 5% of municipal debt for the municipalities served by over six-tenths of affected landfills under the 100 Mg stringency level. However, capital costs are more than double the net municipal debt for the municipalities served by about 2% of the affected landfills at this stringency level.†

In conclusion, the distributional impacts of the §111(d) regulatory alternatives are very low overall for the subset of affected closed and existing landfills. Costs per household in absolute and relative terms are low for the households served by most affected landfills. Similarly, the capital costs of the alternatives under consideration are also low relative to net municipal debt.

8.6.2 Section 111(b) Standards

Table 8-16 in Sec. 8.4.2 indicates that the 25, 100, and 250 Mg stringency levels for the §111(b) Standards affect only 26%, 11%, and 4%, respectively, of all the new landfills in the United States between 1992

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*The landfills having control costs in excess of 10% of local taxes paid by households are the same landfills having relatively high control costs per household. As explained above, the relatively high annualized costs as a percentage of local taxes are attributable to overestimated control costs resulting from overestimated MSW acceptance rates and/or underestimated local taxes as a result of underestimated numbers of households served by these landfills.

†The seven landfills in this category at the 100 Mg stringency level are the result of scaling the estimated capital costs of emissions controls as a percentage of net municipal debt at one landfill in the database. This landfill has an extremely high MSW acceptance rate relative to the number of households it serves. Thus, its high capital costs as a percentage of net municipal debt is probably attributable to overestimated capital costs as a result of an overestimated MSW acceptance rate and/or an underestimate of net municipal debt as a result of an underestimate of the number of municipalities served by this landfill.

TABLE 8-31. NET PRESENT VALUE OF CAPITAL COSTS AS A PERCENTAGE OF NET MUNICIPAL DEBT FOR A SUBSET OF AFFECTED PUBLICLY OWNED CLOSED AND EXISTING LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
National average capital cost as a percent of net municipal debt (%)	1.9	2.4	1.6
Distribution of affected landfills by capital cost as a percent of net municipal debt (%)			
≤ 1	150 (18)	29 (9)	14 (16)
1 to 5	334 (40)	169 (52)	41 (47)
5 to 25	257 (31)	82 (25)	15 (17)
25 to 100	60 (7)	39 (12)	17 (20)
> 100	36 (4)	7 (2)	0 (0)
Total	837 (100)	326 (100)	87 (100)

Note: Numbers in parentheses are percentages. Net present value of capital cost for publicly owned landfills is calculated using a 4 percent discount rate. Details may not add to totals due to rounding.

and 1997. Since the total number of affected new landfills is relatively small, it is very unlikely that any of the stringency levels will affect more than 20% of the small landfills for the reasons described in Section 8.6.1. We confirmed this tentative conclusion with an analysis of the distribution of affected new landfills by their design capacity relative to the total number of new landfills in the same size categories. Thus, the §111(b) Standards under consideration do not require a Regulatory Flexibility Analysis, because they do not affect a significant number of small entities.

Although a Regulatory Flexibility Analysis is not required for the §111(b) Standards under consideration, we examine the distributional impacts of the various stringency levels for a subset of the affected new landfills (i.e., those landfills for which OSW developed household and governmental data for a landfills rulemaking under Subtitle D of RCRA).* These distributional impacts are:

- population of the service area
- annualized control costs per household
- annualized control costs as a percentage of annual local taxes paid by households
- net present value of capital costs as a percentage of net municipal debt (for publicly owned landfills).

We examined these same distributional impacts for the §111(d) regulatory alternatives in Section 8.6.1.

Table 8-32 presents the population of the service area for the subset of affected new landfills. While a third of the affected new landfills for the 25 Mg stringency level serve 10,000 people or less, none of the affected landfills under the other stringency levels serve such small communities. In general, the 25 Mg stringency level affects smaller communities than the 100 and 250 Mg alternatives. More than two-thirds of

*As observed for the closed/existing landfills, the affected new landfills for which OSW data are available are generally smaller than the other affected landfills. However, Student-t tests revealed no significant size differences for any of the stringency levels under consideration.

TABLE 8-32. SERVICE AREA POPULATION FOR A SUBSET OF THE AFFECTED NEW LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
National average service area population (10^3 people)	53.7	93.5	92.5
Distribution of affected landfills by service area population (10^3 people)			
≤ 10	43 (34)	0 (0)	0 (0)
10 to 25	17 (13)	10 (16)	10 (42)
25 to 50	46 (36)	33 (52)	2 (8)
50 to 150	2 (2)	0 (0)	0 (0)
150 to 500	10 (8)	10 (16)	10 (42)
> 500	10 (8)	10 (16)	2 (8)
Total	128 (100)	63 (100)	24 (100)

Note: The numbers in parentheses are percentages. Details may not add to totals due to rounding.

the affected landfills under the 100 Mg stringency level serve communities with 10,000 to 50,000 people.

The national average annualized cost per household for the subset of affected new landfills is below $11 for all three stringency levels (see Table 8-33). As the stringency level decreases, the national average annualized household cost also decreases. Over half the affected landfills under the 100 Mg stringency level have annualized costs per household of $25 or less. However, annualized household costs exceed $50 for 16% of the affected new landfills, ranging as high as $76 per household per year.*

Table 8-34 shows that the national average annualized enterprise cost as a percent of local taxes paid by households is below 1% for the subset of affected new landfills under all three stringency levels. Control costs as a percent of local taxes are under 1% for the households served by almost three-fourths of the affected landfills for the 100 Mg stringency level. Only one-ninth of the affected landfills have control costs as a percent of local taxes paid by households above 10%, with 15% being the maximum.†

The final measure of the distributional impact of the §111(b) Standards under consideration is the net present value of capital costs as a percentage of net municipal debt for a subset of affected, publicly owned, new landfills. Table 8-35 shows that these capital costs are about 2% of net municipal debt as a national average for the affected new landfills. While over four-tenths of the affected new landfills have capital costs under 1% of net municipal debt under the 100 Mg stringency level, the

*The number of households served by landfills having annual household costs above $25 at the 100 Mg stringency level is very low compared to the amount of MSW going into these landfills. So the relatively high costs for these landfills are a result of overestimated control costs caused by overestimated MSW acceptance rates and/or underestimated numbers of households served by these landfills.

†The seven landfills in this category at the 100 Mg stringency level are the result of scaling the annualized costs as a percentage of local taxes per household at one landfill in the database. This landfill has a very low amount of local taxes per household (i.e., $105). Consequently, its costs-compared-to-taxes percentage is relatively high.

TABLE 8-33. ANNUALIZED ENTERPRISE COSTS PER HOUSEHOLD FOR A SUBSET OF THE AFFECTED NEW LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
National average annualized costs per household ($/Household)	**10.56**	**8.55**	**8.37**
Distribution of affected landfills by annualized cost per household ($/Household)			
≤ 5	**29** (23)	**17** (27)	**10** (42)
5 to 10	**22** (17)	**22** (35)	**3** (13)
10 to 25	**24** (19)	**7** (11)	**2** (8)
25 to 50	**22** (17)	**7** (11)	**7** (29)
> 50	**31** (24)	**10** (16)	**2** (8)
Total	**128** (100)	**63** (100)	**24** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent over the life of the landfill. Details may not add to totals due to rounding.

TABLE 8-34. ANNUALIZED ENTERPRISE COST AS A PERCENTAGE OF LOCAL TAXES PAID BY HOUSEHOLDS IN THE SERVICE AREA FOR A SUBSET OF THE AFFECTED NEW LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
National average annualized enterprise cost as a percent of taxes paid by households (%)	0.8	0.7	0.5
Distribution of affected landfills by average annualized cost as a percent of taxes paid by households (%)			
≤ 1	70 (55)	46 (73)	15 (63)
1 to 2.5	34 (27)	7 (11)	7 (29)
2.5 to 10	10 (8)	3 (5)	2 (8)
> 10	14 (11)	7 (11)	0 (0)
Total	128 (100)	63 (100)	24 (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent over the active life of the landfill. Details may not add to totals due to rounding.

TABLE 8-35. NET PRESENT VALUE OF CAPITAL COST AS A PERCENTAGE OF NET MUNICIPAL DEBT FOR A SUBSET OF AFFECTED PUBLICLY OWNED NEW LANDFILLS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
National average capital cost as a percent of net municipal debt (%)	2.1	2.2	1.4
Distribution of affected landfills by capital cost as a percent of net municipal debt (%)			
≤ 1	20 (22)	17 (41)	3 (25)
1 to 2.5	31 (34)	7 (17)	0 (0)
2.5 to 10	22 (24)	7 (17)	7 (58)
> 10	17 (19)	10 (24)	2 (17)
Total	90 (100)	41 (100)	12 (100)

Note: Numbers in parentheses are percentages. Net present value of capital cost for publicly owned landfills is calculated using a 4 percent discount rate. Details may not add to totals due to rounding.

capital costs for almost one-quarter of the affected new landfills under this stringency level are more than 10% of net municipal debt.*

In summary, the distributional impacts of the §111(b) regulatory alternatives are very low overall for the subset of affected new landfills. Costs per household in absolute and relative terms are low for the households served by almost all the affected new landfills. Similarly, the capital costs of the regulatory alternatives under consideration are also low relative to net municipal debt.

8.7 DISCOUNT RATE SENSITIVITY ANALYSIS

Section 8.4 analyzes the net present value of social costs for affected landfills calculated using a two-stage discounting procedure. First, we annualized capital costs over the control period using a 10% discount rate. Then, we discounted the sum of annualized capital costs and annual operating costs at 3% to obtain the net present value of social costs. To investigate the sensitivity of capital costs, operating costs, and total costs to changes in the discount rate, we recalculated social costs using a single discount rate applied to both capital and operating costs.

8.7.1 Section 111(d) Guidelines

Table 8-36 contains the net present value of social costs using a 3% discount rate for affected closed and existing landfills for each §111(d) regulatory alternative under consideration. The costs in this table show a significant decrease in capital costs compared to the costs in Table 8-15 (net present value of social costs using two-stage discounting). Operating costs are discounted using 3% in both cases, so there is no difference between the operating costs presented in these tables. Table 8-37 shows the effect of a 10% discount rate on the net present value of social cost. This table shows a further reduction in capital costs as well as a

*The 10 landfills in this category at the 100 Mg stringency level are the result of scaling the capital costs of two landfills in the database. Both these landfills have extremely high MSW acceptance rates relative to the number of households they serve. So their relatively high capital costs compared to net municipal debt are probably attributable to overestimated capital costs as a result of overestimated MSW acceptance rates and/or an underestimate of net municipal debt as a result of an underestimate of the number of municipalities served by these landfills.

TABLE 8-36. NET PRESENT VALUE OF SOCIAL COSTS FOR AFFECTED CLOSED AND EXISTING LANDFILLS USING A THREE PERCENT DISCOUNT RATE

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National social costs (10^6)			
Capital	2,473	1,764	963
Operating	5,213	2,831	1,514
Total	7,686	4,595	2,477
Average total social cost per affected landfill (10^6)	4.08	5.39	6.42
Distribution of affected landfills by net present value of social costs (10^6)			
≤ 0.5	53	29	7
	(3)	(3)	(2)
0.5 to 1.0	131	46	7
	(7)	(5)	(2)
1.0 to 3.0	850	283	119
	(45)	(33)	(31)
3.0 to 5.0	508	242	135
	(27)	(28)	(35)
5.0 to 10.0	265	185	79
	(14)	(22)	(20)
>10.0	77	68	39
	(4)	(8)	(10)
Total	1,884	853	386
	(100)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of social costs are computed using a 3 percent discount rate. Details may not add to totals due to rounding.

TABLE 8-37. NET PRESENT VALUE OF SOCIAL COSTS FOR AFFECTED CLOSED AND EXISTING LANDFILLS USING A TEN PERCENT DISCOUNT RATE

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National social costs (10^6)			
Capital	**1,812**	**1,318**	**719**
Operating	**1,569**	**906**	**470**
Total	**3,381**	**2,224**	**1,189**
Average total social cost per affected landfill (10^6)	**1.79**	**2.61**	**3.08**
Distribution of affected landfills by net present value of social costs (10^6)			
≤ 0.5	**286** (15)	**111** (13)	**32** (8)
0.5 to 1.0	**683** (32)	**140** (16)	**41** (11)
1.0 to 3.0	**783** (42)	**433** (51)	**232** (60)
3.0 to 5.0	**132** (7)	**104** (12)	**43** (11)
5.0 to 10.0	**53** (3)	**38** (4)	**19** (5)
>10.0	**27** (1)	**27** (3)	**19** (5)
Total	**1,884** (100)	**853** (100)	**386** (100)

Note: Numbers in parentheses are percentages. Net present value of social costs are computed using a 10 percent discount rate. Details may not add to totals due to rounding.

significant reduction in operating costs when compared with the two-stage results. For the 100 Mg stringency level in particular, going from two-stage to single-stage discounting using a 3% discount rate reduces the average cost by 36%; using a 10% discount rate reduces the average cost by 69%.

We estimated annualized social costs by applying an annualization factor to the net present value of total social costs. In all cases we annualized social costs from 1992 to the end of each landfill's control period. Table 8-38 compares costs calculated using two-stage discounting, single-stage discounting at 3%, and single-stage discounting at 10% for affected closed and existing landfills. As expected, two-stage discounting results in higher costs than either of the single-stage calculations. However, annualized costs calculated using a 3% discount rate are lower than annualized costs calculated using a 10% discount rate because of the variable annualization period across affected landfills.

8.7.2 Section 111(b) Standards

Tables 8-39 and 8-40 contain the results of calculating the net present value of social costs for affected new landfills using a 3% and 10% discount rate, respectively. Comparing costs in Table 8-39 with those in Table 8-22 (net present value of social costs using two-stage discounting) shows a decrease in capital costs, but no change in operating costs. Table 8-40 shows a further reduction in capital costs as well as a significant reduction in operating costs when compared with the two-stage results. For the 100 Mg stringency level in particular, going from two-stage to single-stage discounting using 3% reduces the average cost by 37%; using a 10% discount rate reduces the average cost by 83%.

Table 8-41 compares annualized social costs for affected new landfills using different discount rates. As expected, two-stage discounting results in higher costs than the single-stage discounting. Unlike the results for affected closed/existing landfills, the single-stage annualized costs for affected new landfills follow the same pattern as the net present value of costs. That is, annualized costs calculated using a 3% discount rate are higher than those calculated using a 10% discount rate.

TABLE 8-38. TOTAL ANNUALIZED SOCIAL COST FOR AFFECTED CLOSED AND EXISTING LANDFILLS USING VARIOUS DISCOUNT RATES (10^6)

	Stringency Level (Mg NMOC/yr)		
	25	100	250
2-Stage Discounting*	416	297	150
3% Discount Rate**	281	202	99
10% Discount Rate**	358	257	129

* Two-stage discounting involves annualizing each landfill's capital costs at 10% over its control period. Then net present values are computed by discounting annual operating costs and annualized capital costs at 3%. Finally, the net present values are annualized at 3% from 1992 to the end of each landfill's control period and then summed.

** Net present values are annualizd from 1992 to the end of each landfill's control period and then summed.

TABLE 8-39. NET PRESENT VALUE OF SOCIAL COSTS FOR AFFECTED NEW LANDFILLS USING A THREE PERCENT DISCOUNT RATE

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National social costs (10^6)			
Capital	299	215	143
Operating	614	348	200
Total	913	564	343
Average total social cost per affected landfill (10^6)	3.7	5.4	8.4
Distribution of affected landfills by net present value of social costs (10^6)			
≤ 0.5	14	0	0
	(6)	(0)	(0)
0.5 to 1.0	10	0	0
	(4)	(0)	(0)
1.0 to 3.0	131	46	7
	(53)	(44)	(17)
3.0 to 5.0	60	34	22
	(24)	(33)	(54)
5.0 to 10.0	22	14	2
	(9)	(13)	(5)
> 10.0	10	10	10
	(4)	(10)	(24)
Total	247	104	41
	(100)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of social cost is calculated using a 3 percent discount rate. Details may not add to totals due to rounding.

TABLE 8-40. NET PRESENT VALUE OF SOCIAL COSTS FOR AFFECTED NEW LANDFILLS USING A TEN PERCENT DISCOUNT RATE

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National social costs (10^6)			
Capital	**127**	**90**	**58**
Operating	**112**	**63**	**35**
Total	**239**	**154**	**93**
Average total social cost per affected landfill (10^6)	**1.0**	**1.5**	**2.3**
Distribution of affected landfills by net present value of social costs (10^6)			
≤ 0.5	**109** (44)	**41** (39)	**7** (17)
0.5 to 1.0	**68** (28)	**17** (16)	**7** (17)
1.0 to 3.0	**53** (21)	**36** (35)	**17** (41)
3.0 to 5.0	**10** (4)	**3** (3)	**3** (7)
5.0 to 10.0	**7** (3)	**7** (7)	**7** (17)
> 10.0	**0** (0)	**0** (0)	**0** (0)
Total	**247** (100)	**104** (100)	**41** (100)

Note: Numbers in parentheses are percentages. Net present value of social cost is computed using a 10 percent discount rate. Details may not add to totals due to rounding

TABLE 8-41. TOTAL ANNUALIZED SOCIAL COST FOR AFFECTED NEW LANDFILLS USING VARIOUS DISCOUNT RATES (10^6)

	Stringency Level (Mg NMOC/yr)		
	25	100	250
2-Stage Discounting*	45.2	30.2	19.0
3% Discount Rate**	29.6	19.2	11.8
10% Discount Rate**	23.9	15.5	9.3

* Two-stage discounting involves annualizing each landfill's capital costs at 10% over its control period. Then net present values are computed by discounting annual operating costs and annualized capital costs at 3%. Finally, the net present values are annualized at 3% from 1992 to the end of each landfill's control period and then summed.

** Net present values are annualizd from 1992 to the end of each landfill's control period and then summed.

8.8 SUMMARY AND CONCLUSIONS

We focused our economic analysis on the flare option for controlling NMOC emissions from closed/existing and new landfills, although we also presented results for a cost-minimizing energy recovery option for the subset of affected landfills having positive energy recovery costs. The flare option assumes that all affected landfills will control NMOC emissions using flares, which overestimates the actual cost of the regulatory alternatives because some landfills will choose a cheaper energy recovery option. As explained in Section 8.3, our energy recovery option underestimates the costs of the regulatory alternatives at some landfills and overestimates compliance costs at other landfills, with the aggregate effect being unknown. Although EPA emissions controls will increase the likelihood that landfills will select an energy recovery option, there is no way to accurately predict which affected closed/existing and new landfills will actually select this option.

As discussed in Section 8.3, two features of the costing model presented in Chapter 7 are noteworthy for the economic analysis. First, the model assumes that landfills that close between 1987 and 1997 are replaced by an identical landfill serving the same area, while recent evidence indicates that the number of U.S. landfills is actually declining. The model also uses relatively high MSW acceptance rates, which is an important parameter in determining NMOC emissions rates and the cost of emissions controls. These features lead to overestimates of the number of affected landfills, compliance costs, and emissions reductions.

In summary, the actual economic impacts of the §111(d) and 111(b) regulatory alternatives under consideration are probably less than the economic impacts presented in this chapter. Nevertheless, our analysis of these regulatory alternatives leads to several specific conclusions:

- The regulatory alternatives will affect only a small fraction of the closed/existing and new landfills (generally less than 15%), and most of the affected landfills are relatively large.
- The number of affected closed, private landfills, which have no way of generating revenues to cover compliance costs, is small under the flare option and even smaller under the energy recovery option.

- Most control periods are relatively long under the various stringency levels and control options, with most of the control period coming after the closure of affected landfills.

- The national net present value of enterprise costs decreases substantially as the stringency level decreases under both control options for affected closed/existing and new landfills, but the average enterprise cost rises as the stringency level decreases.

- The national annualized enterprise control cost per Mg of MSW is below $1 per Mg for stringency levels under the flare option for affected existing and new landfills and for stringency levels under the energy recovery option for affected new landfills. National annualized enterprise control costs per Mg of MSW range between $1.43/Mg and $2.66/Mg for affected existing landfills under the energy recovery option.

- The costs of the regulatory alternatives are very low for most households--the majority of affected existing landfills have compliance costs under $15 per household per year and the majority of affected new landfills have compliance costs under $10 per household per year.

- While the national cost-effectiveness of almost all the stringency levels under both the flare and energy recovery options is less than $1000 per Mg of NMOC emissions reduction, cost effectiveness varies greatly among affected landfills--much more than is typical for EPA stationary-source regulations.

- The regulatory alternatives under consideration for closed/existing and new landfills will not affect a substantial number of small entities, so a Regulatory Flexibility Analysis is not required for either the §111(d) or 111(b) rulemakings.

- The social costs of the regulatory alternatives for affected closed/existing and new landfills are very sensitive to the discount rate, because of the long control periods under stringency levels for both the flare and energy recovery control options.

In general, the economic impacts of the §111(d) and 111(b) regulatory alternatives on households and municipalities are too small to significantly influence the choice among these alternatives. Privately owned landfills that are already closed and must install emissions controls may be significantly impacted by the regulatory alternatives, because they have no way of recovering their compliance costs. However, there are very few closed, privately owned landfills that are affected under any of the

regulatory alternatives. The control costs of the regulatory alternatives at affected landfills will probably not lead to a significant shift in MSW flows from landfills to municipal waste combustors. Finally, all of the regulatory alternatives will stimulate the adoption of energy recovery technologies at affected landfills.

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9. GUIDANCE FOR IMPLEMENTING THE EMISSION GUIDELINES AND COMPLIANCE SCHEDULE

This chapter, in concert with the entire background information document, has been prepared in accordance with regulations established under Section 111(d) of the Clean Air Act. Under the regulations contained in Subpart B of 40 CFR 60, EPA has established procedures whereby States submit plans to control existing sources of "designated pollutants". Designated pollutants are pollutants which are not included on a list published under Section 108(a) (National Ambient Air Quality Standards) or 112(b)(1)(A) (Hazardous Air Pollutants), but to which a standard of performance for new sources applies under Section 111(b). Under Section 111(d), emission standards are to be adopted by the States and submitted to EPA for approval. The standards would limit the emissions of designated pollutants from existing facilities which, if new, would be subject to the standards of performance for new stationary sources. Such facilities are called designated facilities. The purpose of this chapter is to provide guidance in implementing the emission guidelines and compliance schedules for existing municipal solid waste landfills, and to provide information upon which States may base their plans. The guidance provided in this chapter also applies to new municipal solid waste landfills.

After public review and comment on the draft emission guidelines, a final guideline will be published, and the emission guideline and compliance schedule will be promulgated under Subpart C of 40 CFR 60. The States will then have nine months to develop and submit plans for control of the designated pollutant (municipal landfill gas emissions) from designated facilities. Within four months after the date for submission of such plans, the Administrator will approve or disapprove each plan (or portions thereof). If a State plan (or portion thereof) is disapproved, the Administrator will promulgate a plan (or portion thereof) within six months after the date for plan submission. These and related provisions of Subpart B are basically patterned after Section 110 of the Act and 40 CFR 51 (concerning the adoption and submittal of State implementation plans under Section 110).

As discussed in the preamble to Subpart B (40 FR 5340, November 17, 1975), a distinction is drawn between designated pollutants which may cause or contribute to endangerment of public health (referred to as "health-related pollutants") and those for which adverse effects on public health have not been demonstrated (referred to as "welfare-related pollutants"). For health-related pollutants, emission standards and compliance times in State plans must be at least as stringent as the corresponding emission guidelines and compliance times in EPA's guideline document, but 40 CFR 24.(g) does allow States to adopt and enforce emissions standards and compliance times which are more stringent than those provided in the published guidelines. In addition, as provided in Subpart B, States may apply less stringent requirements for particular designated facilities or classes of facilities, on a case-by-case basis, when economic factors or physical limitations make such less stringent control more reasonable. Such justification may include unreasonable control costs resulting from plant age, location, process design, or the physical impossibility of installing the specified control system. States may also relax compliance time if sufficient justification is provided. Justification for such a relaxation may include unusual time delays caused by unavailability of labor, climatological factors, scarcity of strategic materials, and large work backlogs for vendors or contractors.

For reasons discussed at length in Chapter 2 of this background information document, the Administrator has determined that air emissions from municipal solid waste landfills are health-related pollutants. Briefly, this determination is based on four specific health and welfare effects attributable to these emissions: (1) the adverse health and welfare effects resulting from nonmethane organic emissions, (2) the contribution to global warming of methane emissions, (3) explosion hazard, and (4) odor nuisance. Therefore, the States must develop regulations to control these emissions that are at least as stringent as the final guidelines.

The guidance document mandated under Subpart B must provide specific information to assist States in the development of a plan under Section 111(d). Much of this information is nearly identical for both

new and existing landfills, and has already been provided in this background information document as listed below:

	BID Chapter(s)
Health and welfare effects of air emissions of MSW Landfills	Chapter 2
Landfill gas collection and control techniques	Chapter 4
Control technology efficiency and environmental effects	Chapter 6
National emission reduction potential of guideline	Chapter 6

Rather than duplicate the information which is already provided in this BID, this chapter will focus on the following:

- Time necessary for normal design, installation, and start-up of identified collection and control systems.
- An emission guideline reflective of Best Demonstrated Technology (BDT), and a compliance guideline.

The guidance presented in this section applies to all existing municipal solid waste (MSW) landfills that accepted refuse at any time between November 8, 1987 and the date of proposal of the New Source Performance Standards (NSPS) for MSW landfills. Existing landfills that have capacity available and are not closing prior to accepting any additional refuse are also affected. Landfills which commence construction, or in the absence of construction received refuse, on or after the date of proposal (the NSPS) are defined as new landfills and are subject to the NSPS. The requirements for new landfills are identical to those for existing landfills.

Only a portion of the existing landfills subject to the emission guidelines are required to install air emission control systems. This is the subset of existing municipal solid waste landfills with the greatest potential for adversely impacting public health and welfare. However, many of the landfills included under this definition of designated facility may not pose a significant threat to public health and welfare. The public

health and welfare threat posed by individual municipal solid waste landfills varies widely and more specific guidance on if and when air emission control systems are required at a specific landfill is provided in Section 9.1.

For those facilities required to install landfill gas collection and control systems, specific guidelines for the design and operation of these systems are provided in Sections 9.2, 9.3, and 9.4. The guidelines are separated into two distinctive components: guidelines for effective collection of the municipal landfill gas; and control of the collected landfill gas. Section 9.2 provides guidelines on the design of an effective gas collection system. Section 9.3 provides guidelines on effective operation of the gas collection system. Section 9.4 provides design and operating guidelines for the air emission control device.

Finally, the schedule for compliance with these emission guidelines is presented in Section 9.5. A schedule for compliance is provided for both initial installation of the collection/control system and continued expansion of the collection/control system, as new refuse is placed in active portions of the landfill.

9.1 DETERMINATION OF CONTROL REQUIREMENT

The owner or operator of a designated MSW landfill with a maximum design capacity less than 100,000 Mg refuse must submit a report to the State agency documenting the landfill size. Documentation should include a map or plot of the landfill which provides the size and location of the landfill and identifies all areas where refuse may be landfilled as permitted by the state or county. Documentation should also include the maximum design capacity as specified in the State or county or RCRA permit. If the design capacity has not been specified, then the capacity should be estimated and a copy of the estimation method submitted for review. Upon the State's verification that the maximum design capacity of the landfill is less than 100,000 Mg, the landfill owner/operator is not required to perform further testing reporting, or to install controls. If the design capacity is increased by the addition of new areas, by an increase in the depth of

refuse deposition, by greater compaction, or any other means, an amended design capacity report must be submitted. If the revised capacity exceeds 100,000 Mg, the landfill would then be subject to the additional provision of the guideline.

The owner or operator of a designated MSW landfill with a maximum design capacity greater than 100,000 Mg refuse is required to periodically determine the nonmethane organic compound (NMOC) emission rate from his/her landfill each year, from the effective date of an approved State plan for implementing the emission and compliance guidelines until closure of the landfill. This includes landfills with an existing collection/control system in place. A procedure for determining periodic NMOC emission rate is provided in Section 9.1.1 below. The determined NMOC emission rate is to be reported to the State each year along with supporting data and calculations.

If the NMOC emission rate is determined to be greater than or equal to 150 Mg of NMOC per year, then the landfill owner is required to install a collection system which effectively captures the generated gas and conveys this collected gas to a control system capable of achieving at least a 98 percent reduction in NMOC or a 20 ppmv outlet concentration (dry basis) at 3 percent oxygen. A recovery system can be used to process the landfill gas for subsequent sale, but all atmospheric vents from the recovery system are required to be routed to a control system capable of achieving an overall 98 percent reduction in NMOC or 20 ppmv outlet at 3 percent oxygen. Specific design and operating requirements for the collection and control systems are provided in Section 9.2, 9.3, and 9.4.

At landfills with active collection systems in place, the existing collection system can be used to determine the NMOC mass emission rate only if the system is operating according to the guidelines provided in this chapter. Landfills with passive collection systems in place must have synthetic liners on the bottom, sides, and top of the landfill, as well as, meet the operating guidelines in Section 9.3. Use of existing collection equipment to determine the NMOC mass emission rate is discussed separately in Section 9.1.2.

The owner of a regulated landfill is required to operate the collection and control system, in accordance with the operating guidelines, for a minimum of 15 years, until the landfill is no longer accepting waste and until emissions from the landfill are determined to be less than 150 Mg/year. The procedure for determining when control is no longer required is outlined in Section 9.1.3.

9.1.1 NMOC Emission Rate Determination

The NMOC emission rate is to be determined using the tiered approach as illustrated in Figure 9-1. In the first tier (illustrated in Figure 9-2), the landfill owner or operator is to estimate the NMOC emission rate using the following equation, assuming the acceptance rate is constant from year to year:

$$M_{NMOC} = 2L_o R (e^{-kc} - e^{-kt}) (C_{NMOC})(3.595 \times 10^{-9})$$

where,

M_{NMOC} = mass emission rate of NMOC, Mg/yr
L_o = refuse methane generation potential, m^3/Mg refuse
R = average annual acceptance rate, Mg/yr
k = methane generation rate constant, 1/yr
c = years since closure (c = 0 for active and/or new landfills)
t = age of landfill, yrs
C_{NMOC} = concentration of NMOC, ppmv as hexane
3.595×10^{-9} = conversion factor

The average acceptance rate, R, can be determined by dividing the refuse in place by the age of the landfill. This method for determining the emission rate should only be used for landfills with little or no knowledge of the actual year-by-year refuse acceptance rate. If refuse acceptance rate information is available, the landfill owner should determine the methane generation rate for each yearly submass of refuse and total the results to obtain an accurate overall landfill emission rate. The following equation can be used for the submass approach:

$$Q_i = 2 k L_o M_i (e^{-kti}) (C_{NMOC}) (3.595 \times 10^{-9})$$

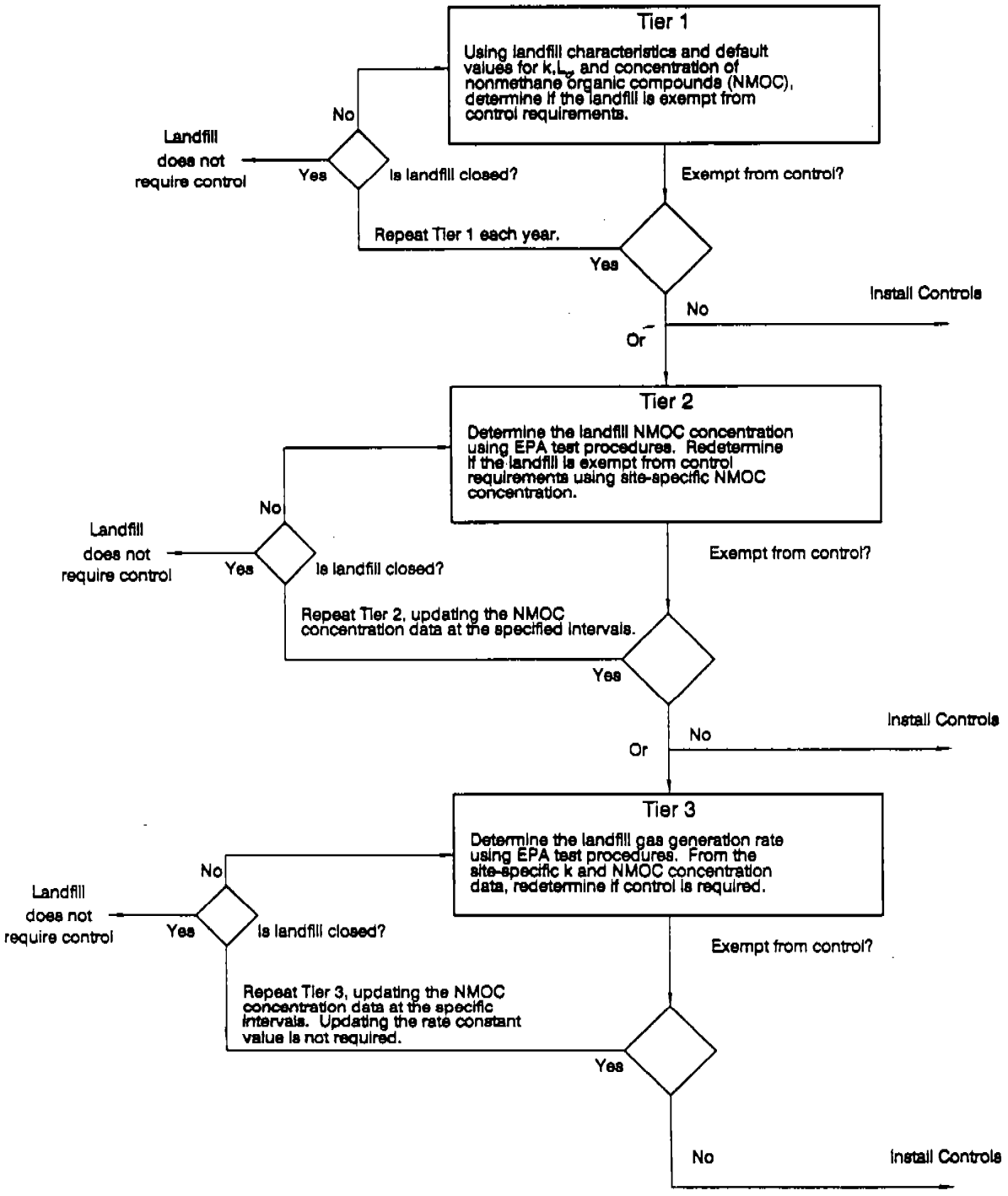


Figure 9-1. Overall Three-Tiered Approach for Determination of Control Requirements

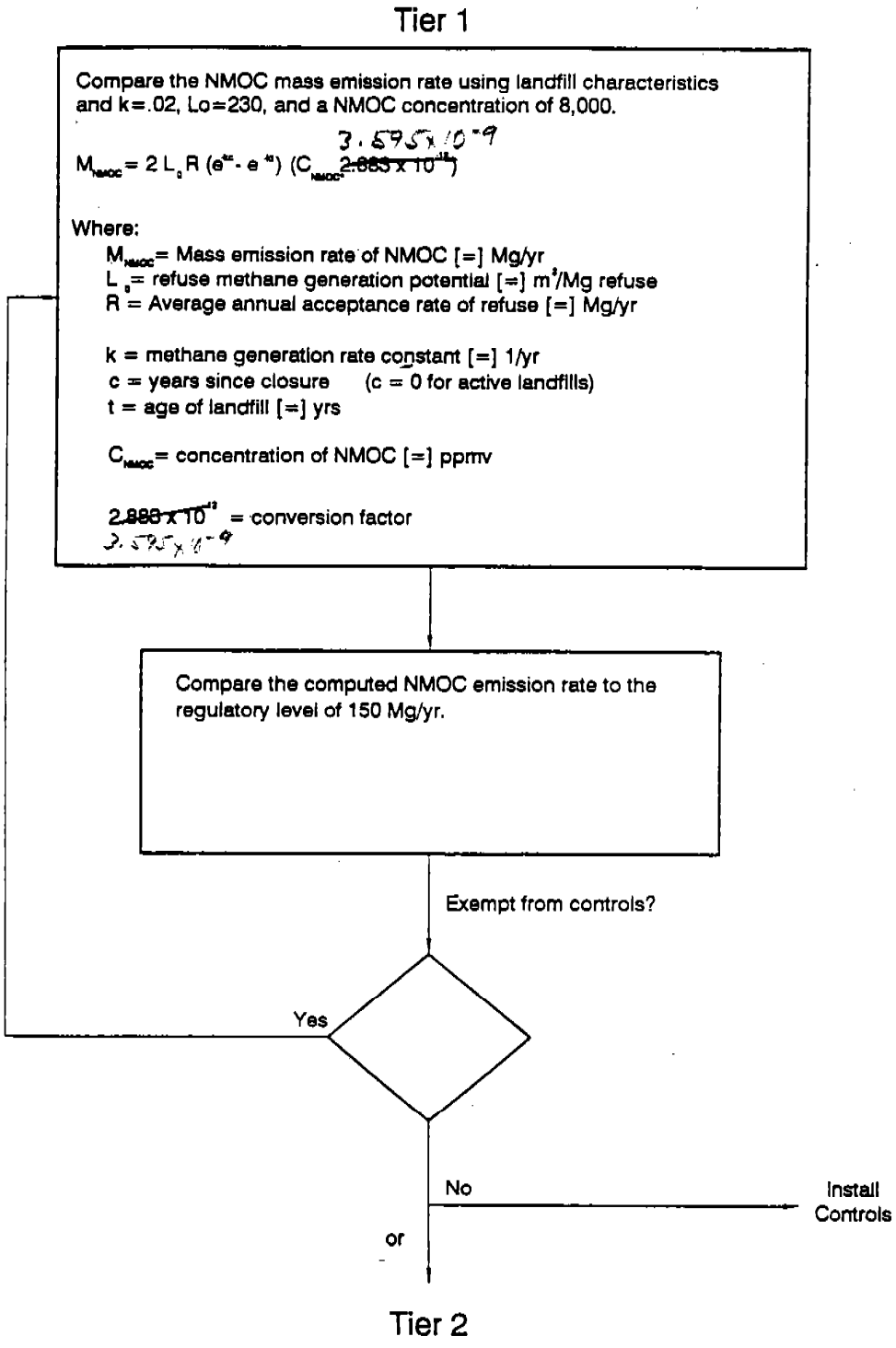


Figure 9-2. Example of Tier 1 Using NMOC Emission Rate Cutoff as the Regulatory Option

where:

Q_i = NMOC emission rate from the i^{th} section, Mg/yr
k = landfill gas generation constant, 1/yr
L_o = methane generation potential, m^3/Mg
M_i = mass of the i^{th} section, Mg
t_i = age of the i^{th} section, yrs
C_{NMOC} = concentration of NMOC, ppmv
3.595×10^{-9} = conversion factor

Regardless of which method is chosen, the nondegradable refuse, such as demolition refuse, should be subtracted from the mass or acceptance rate to avoid overestimating the landfill emission rate. A combination of the two methods may be used if acceptance rate information, such as gate receipts, is only available for a limited time period.

Landfill gas flowrate and/or composition data obtained within 5 years prior to the initial Tier 1 evaluation may be used to determine site-specific values for k and C_{NMOC} provided that the methods used to obtain the data are comparable to EPA Method 2E for flowrate determination and Method 25C for NMOC concentration analysis. The value for k must be computed as outlined in Section 5 of Method 2E regardless of the method used to obtain the raw data. Sufficient documentation of the methods used to obtain these data must be submitted for the State to review. Documentation should include detailed test procedures, test log or data sheets, and any accompanying calculations. In the absence of site-specific data, the values to be used for k, L_o, and NMOC concentration are .02/yr, 230 m^3/Mg, and 8,000 ppmv, respectively. If the calculated NMOC emission rate is greater than 150 Mg/yr, then the landfill owner must either install controls or determine a site-specific NMOC concentration to use in the equation above. If the landfill owner chooses to determine the NMOC concentration, then the steps of Tier 2, illustrated in Figure 9-3, are to be followed. If the NMOC emission rate determined from Tier 2 is greater than 150 Mg/yr, then the landfill owner must either install controls or determine a site-specific gas generation rate constant, k. If the owner chooses to determine k, then the steps of the third tier, illustrated in Figure 9-4, are to be followed. If

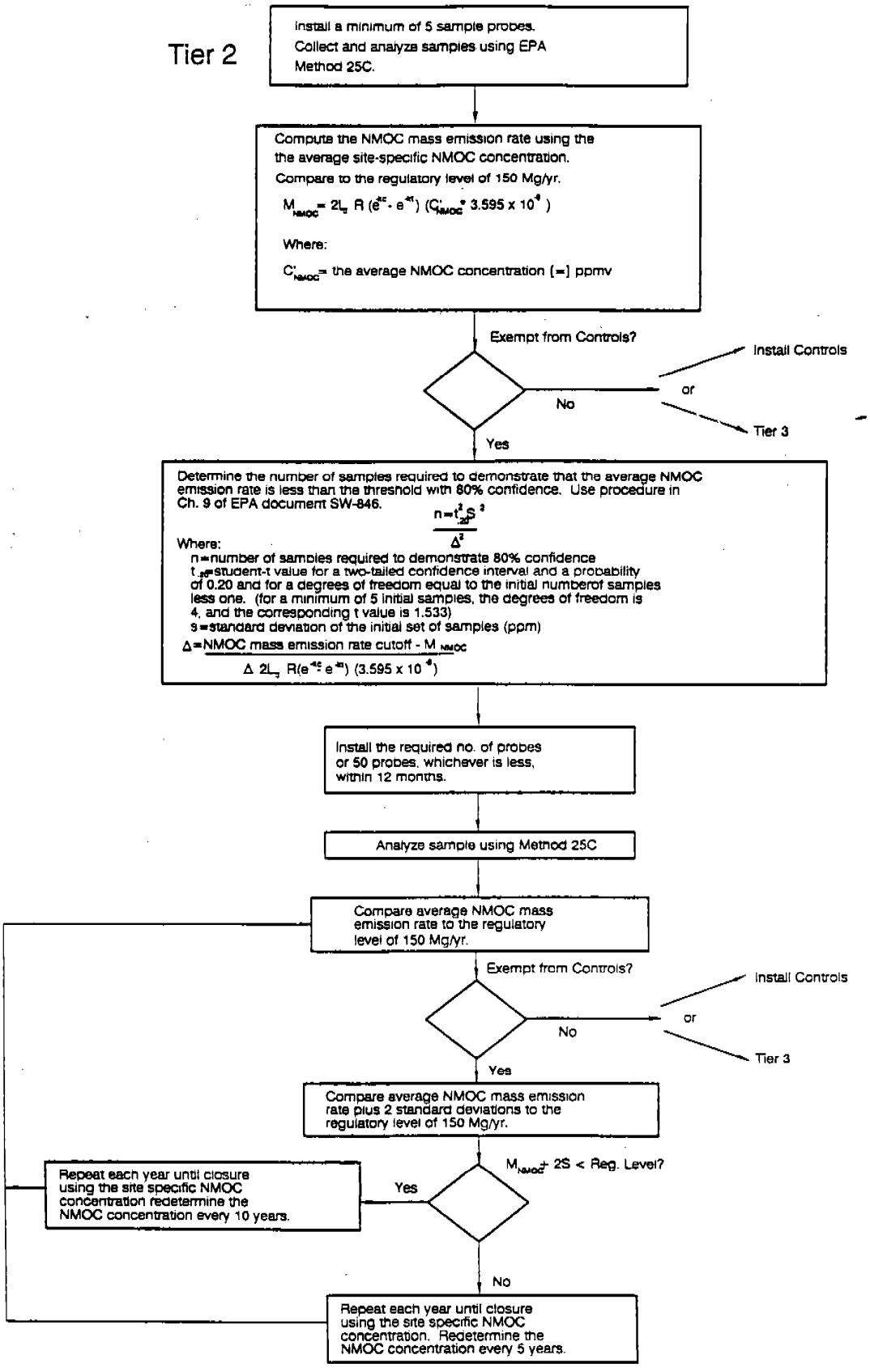


Figure 9-3. Example of Tier 2 Using NMOC Emission Rate Cutoff as the Regulatory Option

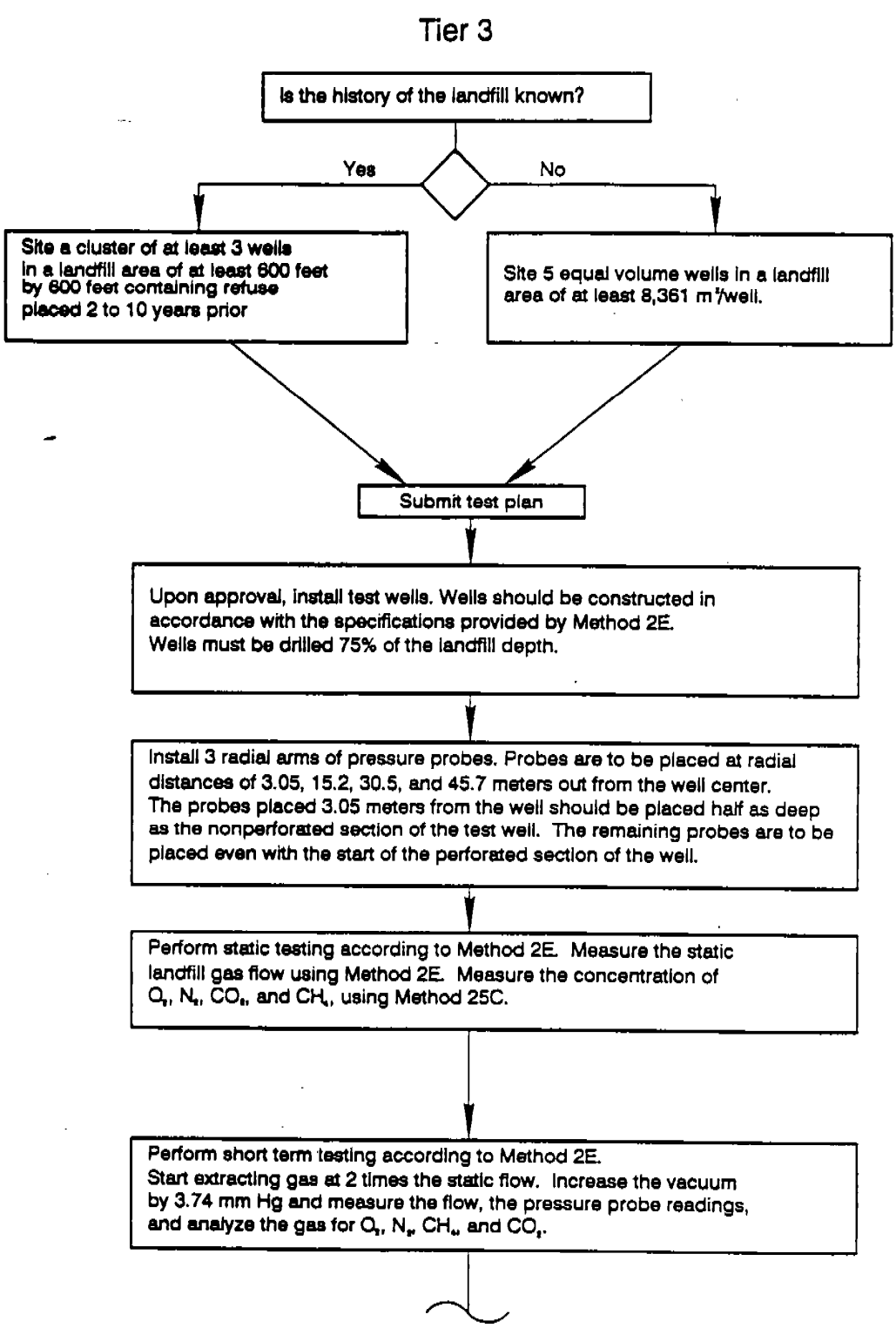
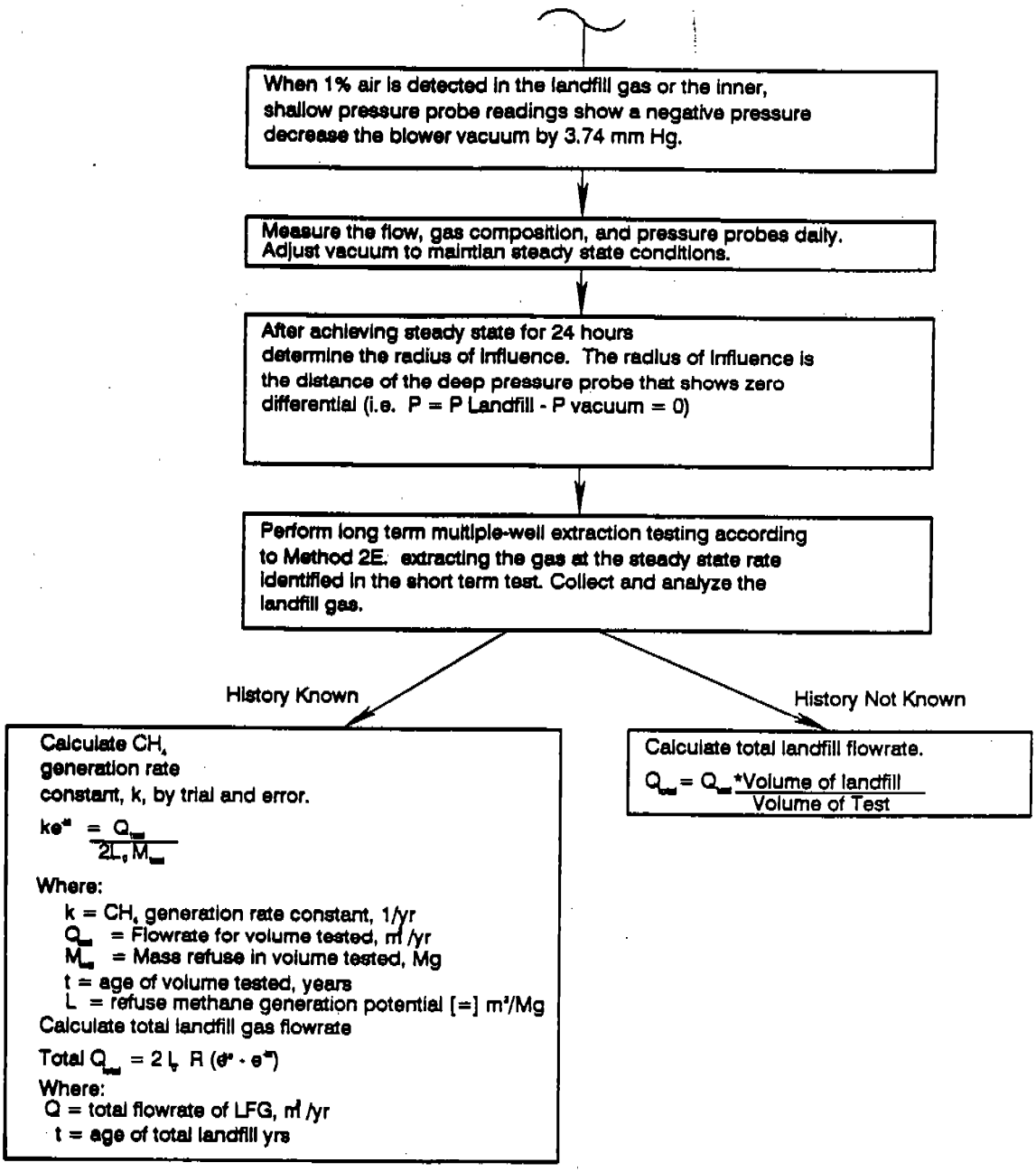


Figure 9-4. Example of Tier 3 Using NMOC Emission Rate Cutoff as the Regulatory Option


When 1% air is detected in the landfill gas or the inner, shallow pressure probe readings show a negative pressure decrease the blower vacuum by 3.74 mm Hg.
Measure the flow, gas composition, and pressure probes daily. Adjust vacuum to maintian steady state conditions.
After achieving steady state for 24 hours determine the radius of influence. The radius of influence is the distance of the deep pressure probe that shows zero differential (i.e. P = P Landfill - P vacuum = 0)
Perform long term multiple-well extraction testing according to Method 2E. extracting the gas at the steady state rate identified in the short term test. Collect and analyze the landfill gas.
History Known
History Not Known
Calculate CH4 generation rate constant, k, by trial and error.
ke^-kt = Q_mm / 2L_o M_mm
Where:
k = CH4 generation rate constant, 1/yr
Q_mm = Flowrate for volume tested, m3/yr
M_mm = Mass refuse in volume tested, Mg
t = age of volume tested, years
L = refuse methane generation potential [=] m3/Mg
Calculate total landfill gas flowrate
Total Q_mm = 2 L_o R (e^-kt - e^-kt)
Where:
Q = total flowrate of LFG, m3/yr
t = age of total landfill yrs
Calculate total landfill flowrate.
Q_mm = Q_mm * Volume of landfill / Volume of Test

the NMOC emission rate determined in Tier 3 is greater than 150 Mg/yr, then controls must be installed in accordance with the compliance schedule provided in Section 9.5.

In determining the NMOC emission rate, the entire municipal solid waste landfill is considered rather than any subdivision of the landfill, such as an individual cell. The entire landfill is defined as the contiguous landfill property designated for solid waste disposal irrespective of subdividing access roads. This includes closed portions of the landfill (no longer accepting refuse), as well as active portions. Additionally, multiple ownership does not affect the definition of a municipal solid waste landfill.

9.1.2 Landfills with a Collection/Control System In Place Prior to Regulation

An owner of a landfill with an existing collection/control system in place has the option of using the tiered approach or using the existing equipment to determine the NMOC mass emission rate for comparison against the standard. The landfill owner may use existing landfill gas collection equipment to determine the NMOC mass emission rate, only if the collection system meets the operating guidelines in Section 9.3. That is, the landfill owner must be able to show that there is not excessive air infiltration and that there is not a positive pressure at each well head. An excessive influx of air may result in an overestimation of the landfill gas flowrate. A positive pressure reading at the well head with a fully open valve means additional wells are required. The landfill owner must also be able to document that the collection system is effectively collecting landfill gas from all gas producing areas of the landfill.

The NMOC mass emission rate can be determined by measuring the total landfill gas flowrate and by determining the NMOC concentration of the gas. The flowrate measurement should be taken at the common header pipe that leads to the control device using an orifice meter as described in Method 2E. The NMOC concentration can be determined by collecting and analyzing a landfill gas sample from the common header pipe using Method 25C. The average NMOC concentration of at least three gas samples

should be used. The following equation can be used to determine the annual NMOC mass emission rate:

$$M_{NMOC} = 1.89 \times 10^{-3} Q_{LFG} C_{NMOC}$$

where:

M_{NMOC} = mass emission rate of NMOC, Mg/yr
Q_{LFG} = flowrate of landfill gas, m^3/min
C_{NMOC} = NMOC concentration, ppmv

If the resulting NMOC mass emission rate is greater than 150 Mg NMOC/yr, then the landfill should continue to operate the collection/control system according to the guidelines outlined in Section 9.3. It is not mandatory that existing collection system meet all of the design specifications included in 9.2, if the collection system meets the operating guidelines provided in Section 9.3. If the NMOC emission rate is less than 150 Mg/yr, then the landfill is exempt from control for that year only. The NMOC mass emission rate should be determined periodically until the landfill closes, and if the NMOC emission rate exceeds 150 Mg/yr at any time, controls should be operated until the requirements of 9.1.3 are met.

9.1.3 Guidelines for Discontinuing Control

Control of landfill air emissions is no longer required when it meets all of the following criteria:

- Controls have been in place and operated for at least 15 years;
- The landfill is no longer accepting waste; and
- Emissions from the landfill are less than 150 Mg/yr.

The annual NMOC mass emission rate must be less than 150 Mg/yr for three consecutive testing periods, between 90 and 180 days apart, in order to meet the emission criteria above.

The emission rate is to be determined by measuring the total landfill gas flowrate and by determining the NMOC concentration of the gas. The flowrate measurement should be taken at the common header pipe that leads to the control device using an orifice meter as described in Method 2E. The NMOC concentration should be determined by collecting and analyzing a gas

sample from the common header pipe using Method 25c. The following equation should be used to determine the annual NMOC mass emission rate for each set of flow and NMOC concentration measurements.

$$M_{NMOC} = 1.89 \times 10^{-3} Q_{LFG} C_{NMOC}$$

where:

M_{NMOC} = mass emission rate of NMOC, Mg/yr
Q_{LFG} = flowrate of landfill gas, m^3/min
C_{NMOC} = NMOC concentration, ppmv

Again, the determined NMOC mass emission rate should be less than 150 Mg/yr for three consecutive quarters before operation of the control system is discontinued.

9.2 DESIGN GUIDELINES FOR GAS COLLECTION SYSTEMS

Landfill gas collection systems can be categorized into two basic types: active collection systems and passive collection systems. Active collection systems employ mechanical blowers or compressors to provide a pressure gradient in order to extract the landfill gas. The systems can be further categorized into two types: vertical well systems and horizontal trench systems. Passive systems rely on the natural pressure gradient (i.e., internal landfill pressure created due to landfill gas generation) or concentration gradient to convey the landfill gas to the atmosphere or to a control system.

The Agency has evaluated the effectiveness of both active and passive collection systems and has concluded that well designed active collection systems are the most effective means of collecting landfill gas.[1] The Agency also found that well designed passive collection systems can approximate the efficiency of an active system when used in conjunction with synthetic liners and caps. Generally, passive collection systems have much lower collection efficiency than active collection systems since they rely on natural pressure gradient (i.e., internal landfill pressure created due to landfill gas generation) or concentration gradient rather than the pressure gradient induced by a blower or compressor. However, the Agency's study revealed that passive collection systems can be nearly equivalent, if the landfill design includes synthetic liners on the top, bottom, and sides

of the landfill. Landfills with highly impermeable containment such as canyons or quarries may also be well-suited for passive systems, however, these should be evaluated on a case-by-case basis taking into account fissures and cracks that may exist in the containment.

Selection of a collection system type often depends on the landfill characteristics and landfill operating practices. For example, if a landfill employs a layer-by-layer landfilling method (as compared to cell-by-cell methods), an active horizontal trench collection system may be preferred over an active vertical well collection system due to the ease of collection system installation. However, if the water table extends into the refuse, horizontal trench systems have a tendency to flood, thus decreasing the collection efficiency. Applications, advantages, and disadvantages of different collection systems are summarized in Table 9-1.

For landfills required to install collection and control systems, the owner of the landfill is first required to develop the collection system design. The design must be based on the specifications for an active vertical collection system provided in Section 60.758 of the NSPS. Alternatively, an owner or operator who wishes to use a collection system not based on those specifications must submit a plan to the State Agency for review. Alternative designs would still need to satisfy the four criteria of an effective collection system provided below, and the plans submitted for review must address each of the four criteria. Provisions for expanding the system as waste accumulates must be indicated in the plan. This plan should include the type of collection system (active or passive), an estimate of the maximum expected gas collection rate, a plot plan of the entire landfill with proposed well placements and estimated radii of influence, and specifications for gas moving equipment. If a passive system is proposed, containment specifications and the estimated collection/control system pressure drop should also be provided. This plan is to be reviewed by the State and, upon approval of the plan, the collection system is to be installed in accordance with the compliance schedule provided in Section 9.5.

The landfill gas collection system must be designed to provide effective collection of the landfill gas. In order for the landfill gas

TABLE 9-1 COMPARISON OF VARIOUS COLLECTION SYSTEMS

Collection system type	Preferred applications	Advantages	Disadvantages
Active Collection Systems			
Vertical Wells	Landfills employing cell-by-cell landfilling methods	Cheaper or equivalent in costs when compared to horizontal trench systems	Difficult to install and operate on the active face of the landfill (may have to replace wells destroyed by heavy operative equipment)
Horizontal Trench	Landfills employing layer-by-layer landfilling methods Landfills with natural depressions such as canyon	Easy to install since drilling is not required Convenient to install and operate on the active face of the landfill	The bottom trench layer has higher tendency to collapse and difficult to repair once it collapses Has tendency to flood easily if water table is high Difficult to maintain uniform vacuum along the length (or width) of the landfill
Passive Collection Systems			
	Landfills with good containment (side liners and cap) Landfills with only gas migration problems	Cheaper to install and maintain if only a few wells are required	Collection efficiency is generally much lower than active collection systems Costs is generally higher than active systems when designed for the same collection efficiency

collection system to be considered effective, it must: (1) provide collection of landfill gas from all gas generating areas within the landfill; (2) provide well spacing adequate to collect landfill gas from all areas of the landfill without overdraw of air into the landfill; (3) provide a gas moving system capable of handling the maximum expected gas flow; and (4) include monitoring and adjustment provisions to facilitate effective operation. Additionally, the gas collection wells are to be constructed in conformance with certain specifications.

The first requirement, collection of landfill gas from all gas producing areas, is common to all collection system types. The gas collection system must be designed to provide gas collection from all gas producing areas of the landfill which contain refuse that is at least two years old. Areas known to contain asbestos should not be included in the collection system design. The collection system should also be designed to extend into each new area of the landfill within two years of the initial placement of refuse in that area. For shallow areas, extraction wells can be installed and vertically extended as more refuse is added. Since this type of installation may make filling that portion of the landfill difficult, it is recommended that the landfill owner/operator manage the filling pattern to avoid shallow sections that meet the age criteria.

Certain landfills will contain sections of refuse that do not produce a significant amount of landfill gas, either due to the age of the refuse or the type of refuse. These "nondegradable" sections may be excluded from control if the landfill owner or operator can show that emissions from the all such sections contribute less than one percent to the total amount of emissions from the landfill. Emissions from a given section may be computed using the following equation:

$$Q_i = 2\ k\ L_o\ M_i\ (e^{-kt_i})\ (C_{NMOC})\ (3.595 \times 10^{-9})$$

where:

Q_i = NMOC emission rate from the i^{th} section, Mg/yr
k = landfill gas generation constant, 1/yr
L_o = methane generation potential, m^3/Mg
M_i = mass of the degradable refuse in the i^{th} section, Mg

t_i = age of the refuse in the i^{th} section, yrs

C_{NMOC} = concentration of NMOC, ppmv

3.595×10^{-9} = conversion factor

The values for k, L_o, and C_{NMOC} used in the tiered procedure should be used if a specific k and C_{NMOC} for the given section has not been determined through field testing. The mass of the nondegradable refuse contained within the given section may be subtracted from the total mass of the section when estimating emissions. The landfill owner or operator should provide records showing the amount and type of refuse claimed as nondegradable and the location of such refuse within the landfill. If more than one section is proposed for exclusion from control, an emissions estimate should be made for each section. The sum of the emissions from all the potentially excluded sections must be less than one percent of the total landfill emissions to qualify for exemption.

The remaining requirements of an effective collection system, adequate well spacing, flow capacity, and well construction are somewhat specific to the type of collection system selected. These requirements are addressed in the following sections specific to each collection system type.

9.2.1 Design Guidelines for Active Vertical Collection Systems

Four design features of the proposed vertical collection system must be evaluated by the owner or operator and by the State reviewer when a collection system design plan is submitted for review to ensure that an effective collection system is installed. These are the proposed well spacing, the proposed well construction, provisions for well monitoring and adjustment, and capacity of the gas mover system. Each of these design features are addressed below.

9.2.1.1 Vertical Well Spacing. The desired method for determining effective well spacing at a specific landfill is the use of field measurement data. EPA Method 2E, prescribed in Tier 3 of the NMOC emission rate determination, can be used to determine the average stabilized radius of influence for both perimeter wells and interior wells. If such a determination has been made using EPA Method 2E, the determined radii of influence are to be used in setting the well spacing. Wells placed along the perimeter of the landfill (but, still in the refuse) are to be placed no

more than the perimeter radius of influence from the perimeter and no more than two times the perimeter radius of influence apart. As illustrated in Figure 9-5, a helpful technique is to site the location of each well and draw a circle with radius equal to the radius of influence (perimeter radius of influence for perimeter wells and interior radius of influence for interior wells). Once the perimeter wells are sited on the landfill plot plan, the interior wells are to be sited at no more than two times the interior radius of influence in an orientation such that essentially all areas of the landfill are covered by the radii of influence. Figure 9-5 provides an illustrative demonstration of this concept.

In situations where the landfill owner chooses not to perform EPA Method 2E, the well spacing must be determined based on theoretical concepts. In order to evaluate the proposed well spacing for these situations, it is important to understand the relationship between applied vacuum (well vacuum) and air infiltration. It is advantageous to apply higher vacuum in order to maximize the radius influence and minimize the number of wells required. But, higher vacuum leads to increased air infiltration. Consequently, excessive air infiltration (greater than one to two percent air) kills the methanogens which produce the landfill gas, supports aerobic decomposition of the refuse, and can potentially lead to a landfill fire.

In the absence of field measurement data, reasonableness of the proposed well vacuum must first be reviewed. The maximum vacuum that can be applied at the well, without excessive air infiltration, is restricted primarily by three landfill characteristics: the landfill depth, gas permeability of the cover or cap material, and the cover thickness. Assuming a 2 ft final cover as required under RCRA, the theoretical vacuum that can be applied without excessive air infiltration is presented in Figure 9-6 for three cover materials. As illustrated in the figure, the maximum vacuum is greatly a function of landfill depth. The maximum vacuum that can be applied is also dependent on the landfill gas generation rate. However, since this can only be determined for a specific site through field measurement, the figure is based on the Scholl-Canyon model with a rate constant (k) of .02 $years^{-1}$ and an ultimate gas generation constant (L_0) of

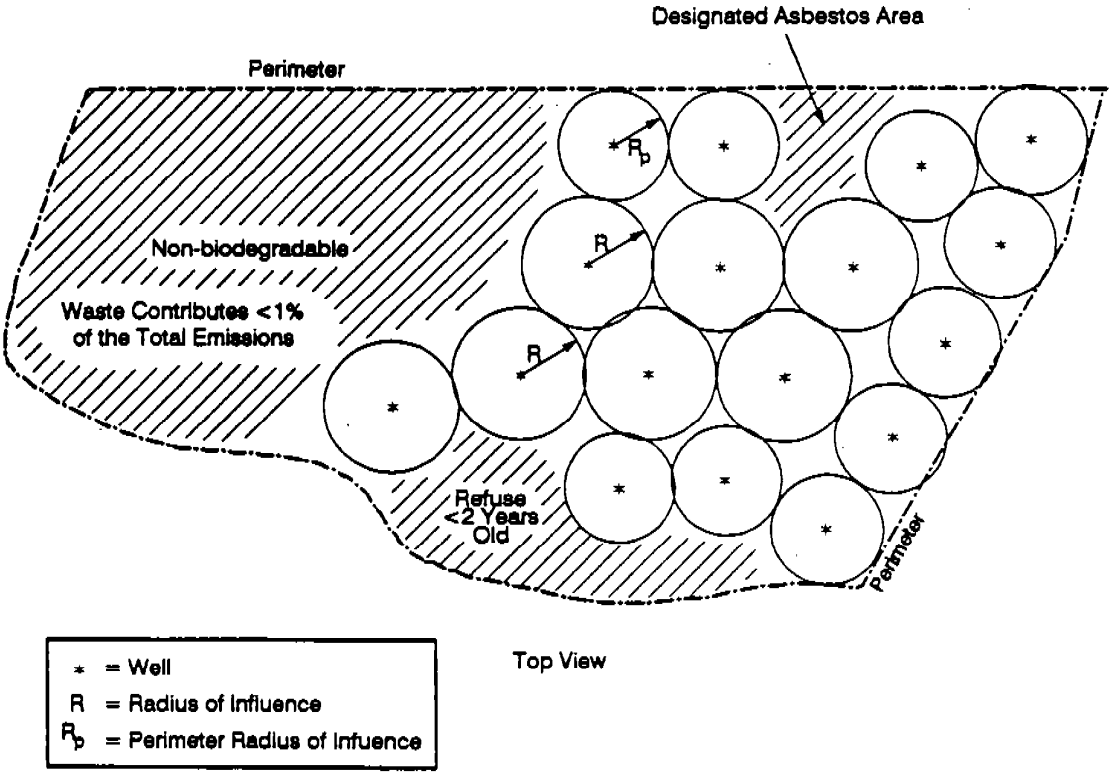


Figure 9-5. Technique for siting wells.

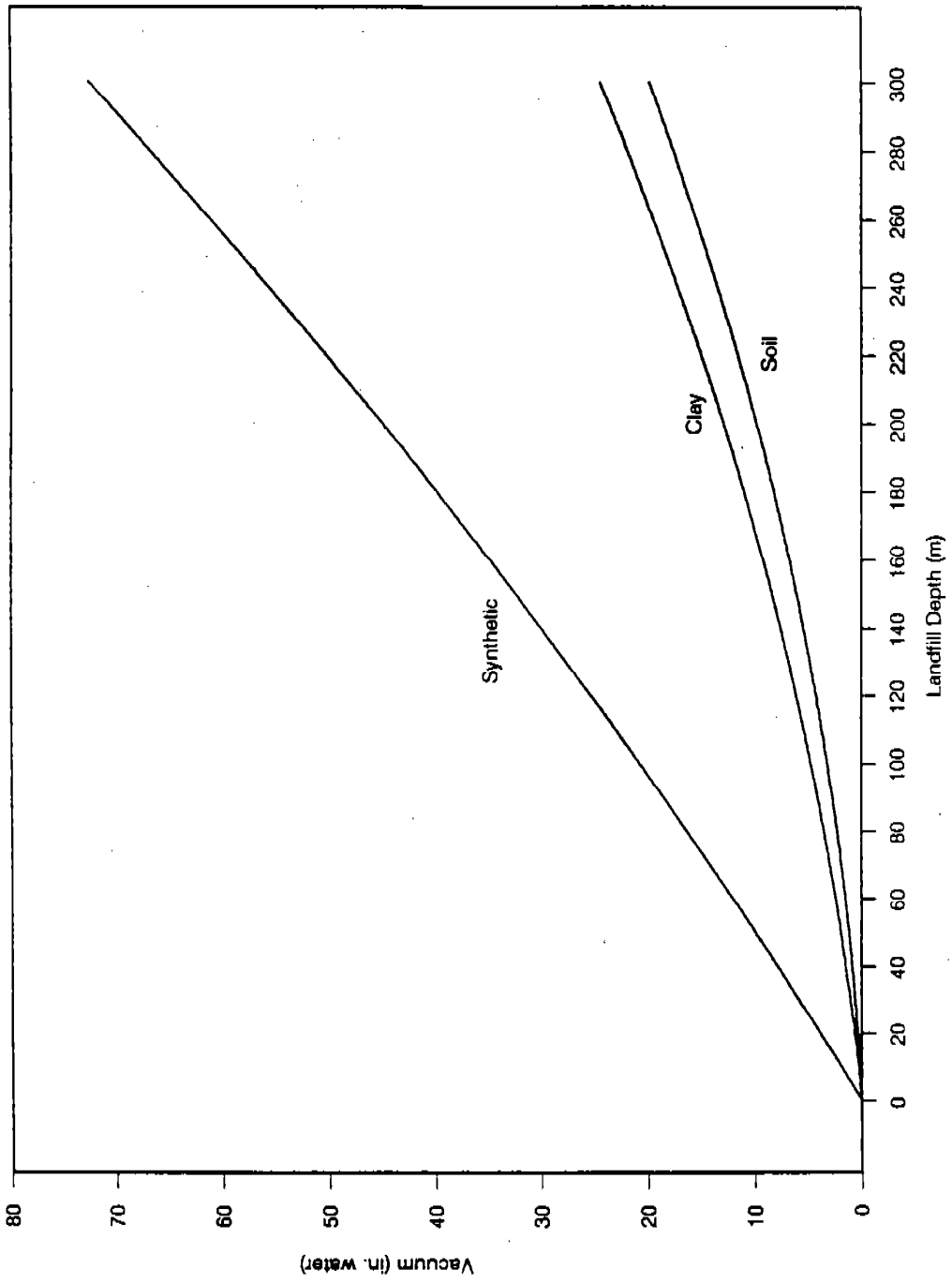


Figure 9-6. Maximum Blower Vacuum as a Function of Landfill Depth for Three Cover Types

230 m^3/Mg. The theoretical basis for Figure 9-6 is further described in Appendix G.

In cases where field measurement is not performed, the proposed well vacuum should be compared to the predicted maximum from Figure 9-6. If the proposed vacuum is less than or equal to that indicated in Figure 9-6, then the proposed value can be used to determine the radius of influence from Figure 9-7. If the proposed well vacuum is greater than the maximum indicated in Figure 9-6, then the value obtained from Figure 9-6 should be used to determine the radius of influence from Figure 9-7. Consistent with the theoretical correlation presented for maximum well vacuum, the correlation presented in Figure 9-7 for radius of influence is based on the Scholl-Canyon model with a k of .02 $years^{-1}$ and L_0 of 230 m^3/Mg. The theoretical basis and calculations are detailed in Appendix G.

Once the radius of influence is determined, the proposed well placement can be evaluated. Identical to the criteria outlined above when using a field measured radius of influence, the wells are to be sited along the perimeter of the landfill no more than the radius of influence from the landfill perimeter and two times the radius of influence apart. Once the perimeter wells are sited, then wells are to be sited throughout the interior of the landfill, at a distance of no more than two times the radius of influence. The only difference in this technique and the one described above is that a single radius of influence is used in siting both perimeter and interior wells.

9.2.1.2 Well Construction. The landfill gas extraction well is to be constructed of polyvinyl chloride (PVC), high density polyethylene (HDPE) pipe, fiberglass, stainless steel, or other suitable nonporous material, at least 3 inches in diameter. The well should extend from the landfill surface to at least 75 percent of the landfill depth. It is recommended that the bottom two thirds of the pipe be perforated with 1/2 inch diameter holes spaced at 90 degrees every 6 inches. Slotted pipe having equivalent perforations is also suitable. The pipe should be placed in the center of a 2 ft diameter bore and backfilled with gravel to a level 1 ft above the perforated section. A 4 ft layer of backfill material should be placed on top of the gravel followed by at least 3 ft of bentonite. The remainder of

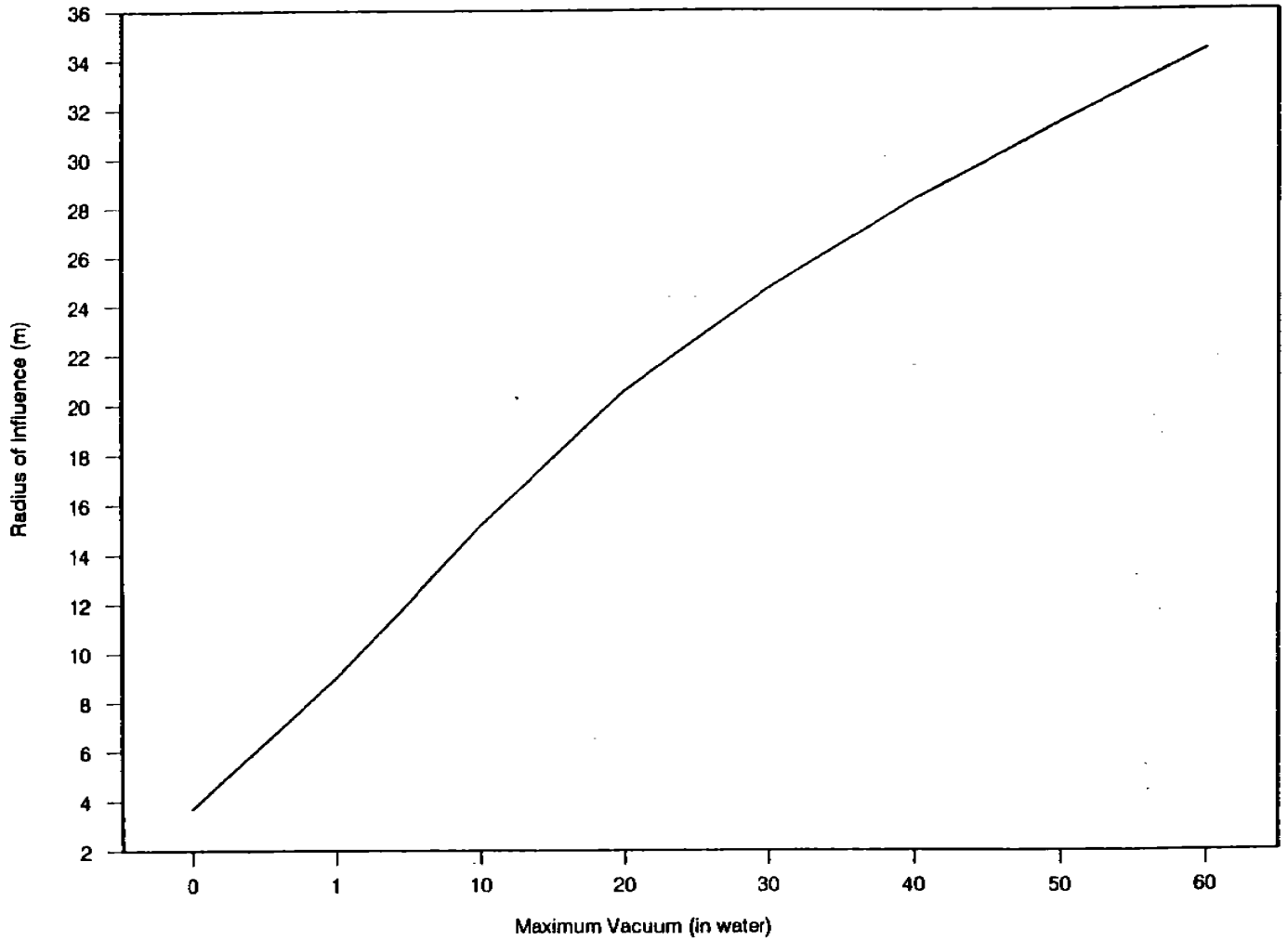


Figure 9-7. Estimated Radius of Influence as a Function of blower Vacuum

the bore can be backfilled with cover material or a material of equal or lower permeability.

9.2.1.3 Monitoring and Adjustment Design Provisions. To facilitate periodic well monitoring and adjustment, the well head should be equipped with a valve, flanges, gaskets, connectors and access couplings. The well assembly should also include at least one sample port that can be used to monitor pressure or collect gas samples periodically. The extraction well assembly and well head assembly are illustrated in Figure 9-8.

The well head may be connected to the collection header pipes below or above the landfill surface. The advantage of installing header pipes above ground is the ease of maintenance and operation. The disadvantage is the higher probability of damaging header pipes with landfill operating equipment and the possibility of blockage in the pipeline due to the condensate freezing in areas with severe winters.

9.2.1.4 Gas Mover Sizing. The gas mover (fan, blower or compressor) system should be designed to handle the peak landfill gas flowrate over the life of the gas moving equipment. This attribute can be evaluated by first projecting the peak landfill gas flowrate and comparing this flow to the proposed equipment specifications. The peak gas flow rate can be projected using the following expression:

$$\text{Peak Flow } [m^3/yr] = 2L_o R (1 - e^{-kt})$$

where,

L_o = refuse methane generation potential, m^3/Mg refuse
R = average annual acceptance rate, Mg/yr
k = methane generation rate constant, 1/yr
t = age of the landfill plus the gas mover equipment life or active life of the landfill, which ever is less, in years

A value of 230 m^3/Mg is recommended for L_o. If Method 2E has been performed, the value of k determined from the test should be used; if not, a value of .02 $years^{-1}$ is recommended.

9.2.2 Design Guidelines for Active Horizontal Collection Systems

Four design features of the proposed horizontal collection system should be evaluated by the State reviewer to ensure that an effective

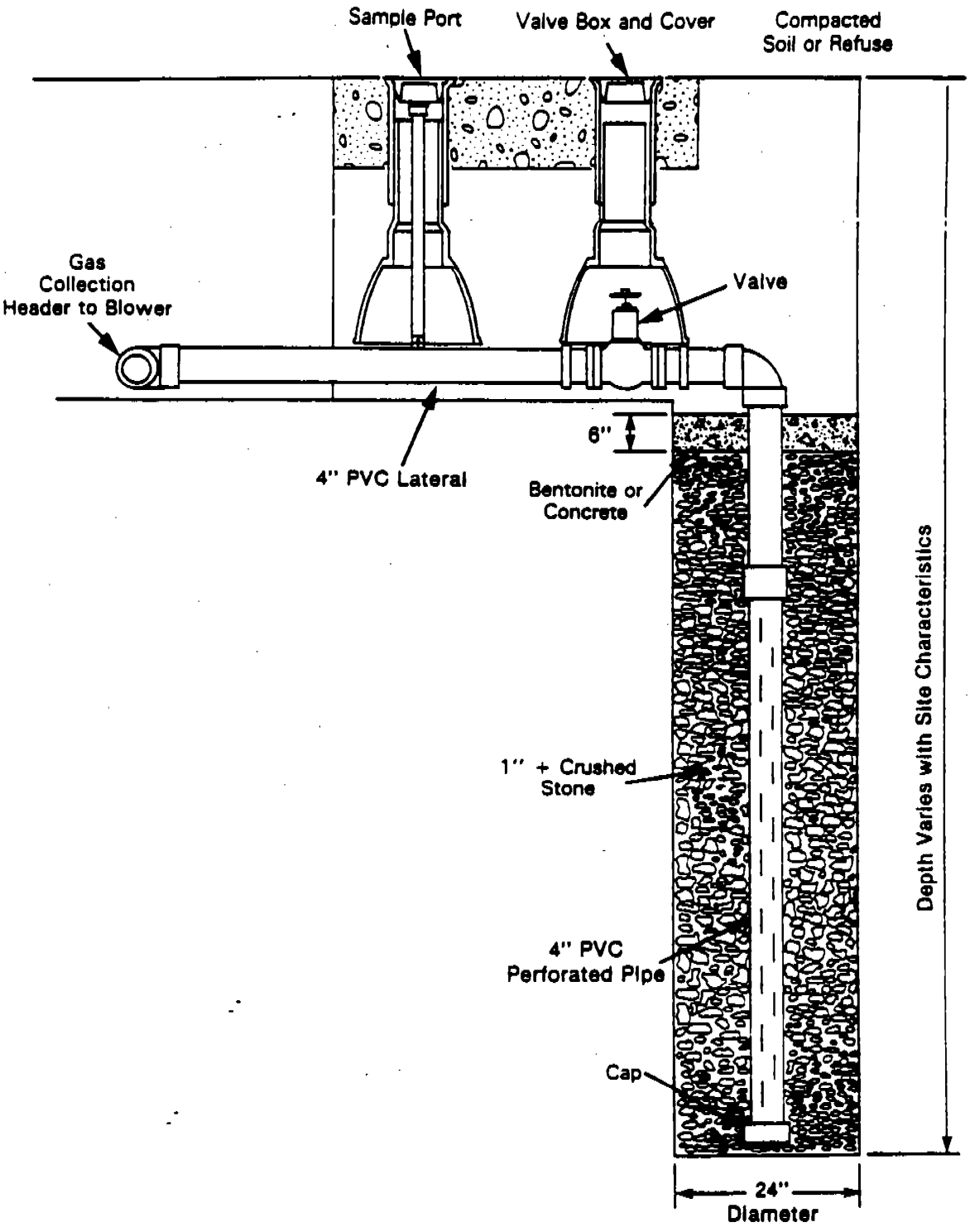


Figure 9-8. Gas extraction well and well head assembly.

collection system is installed. These are the proposed well spacing, the proposed trench construction, provisions for trench monitoring and adjustment, and capacity of the gas mover system. Each of these design features are addressed below.

9.2.2.1 Horizontal Trench Spacing. The preferred method for determining effective trench spacing at a specific landfill is the use of field measurement data. Although EPA Method 2E is based on a vertical well test, results of this method can be used to determine radius of influence in the horizontal direction. If such a determination has been made using EPA Method 2E, the determined radius of influence is to be used in setting the horizontal spacing. The trenches should be spaced at a distance of no more than two times the measured radius of influence (measured radius of influence for internal vertical wells) apart. The vertical spacing of trenches, however should be closer. Since compaction of the refuse causes refuse permeability to be lower in the vertical direction, influence of the trench is less in the vertical direction than in the horizontal direction. A vertical spacing of one forth the horizontal spacing is recommended to account for lower permeability in the vertical direction.

In situations where the landfill owner chooses not to perform EPA Method 2E, the well spacing is to be determined based on the same theoretical concepts presented in Section 9.2.1.1 for vertical well spacing. Using the proposed trench vacuum, the theoretical radius of influence in the horizontal direction can be obtained from Figure 9-7. This radius of influence is to be used identically to the interior radius of influence determined discussed above. The trenches are to be spaced no more than two times the theoretical radius of influence apart horizontally, and vertically no more than one-half the theoretical radius of influence.

9.2.2.2 Trench Construction. The horizontal trenches may be constructed of PVC, HDPE, corrugated steel, or other suitable nonporous material. In order to minimize the collapse of the trenches due to the refuse accumulation and/or landfill operation equipment, some employ alternating pipe connections which typically consist of pipes with adjacent diameters (e.g., 8" and 10", 10" and 12", etc.) loosely fitted together. Loose fitting pipes of different diameters allow landfill gas to freely flow

through yet also handles the stress due to the refuse weight and/or equipment better than straight pipe connections. Some landfill owners prefer using corrugated steel pipes since the heat of the landfill tends to reduce the stress strength of PVC or HDPE pipes. Typical construction of the horizontal trench collection system is illustrated in Figure 9-9.

9.2.2.3 Monitoring and Adjustment Design Provisions. To facilitate periodic trench monitoring and adjustment, each layer of trenches should be connected to a common header leg that extends to the surface and is equipped with a valve, flanges, gaskets, connectors and access couplings. The header leg assembly should also include at least one sample port that can be used to monitor pressure or collect gas samples periodically. The trench header assembly should allow for controlling individual layers of trenches.

9.2.1.4 Gas Mover Sizing. The gas mover (fan, blower or compressor) system should be designed to handle the peak landfill gas flowrate over the life of the gas moving equipment. Identical to vertical well collection systems, this attribute can be evaluated by first projecting the peak landfill gas flowrate and comparing this flow to the proposed equipment specifications. The peak gas flow rate can be projected using the following expression:

$$\text{Peak Flow } [m^3/yr] = 2L_0 R (1 - e^{-kt})$$

where,

L_0 = refuse methane generation potential, m^3/Mg refuse
R = average annual acceptance rate, Mg/yr
k = methane generation rate constant, 1/yr
t = age of the landfill plus the gas mover equip. life or active life of the landfill, which ever is less, in years

A value of 230 m^3 is recommended for L_0. If Method 2E has been performed, the value of k determined from the test should be used; if not, a value of .02 $years^{-1}$ is recommended.

9.2.3 Design of Passive Collection Systems

As indicated above, passive systems are accepted as BDT only when combined with a synthetic liner on the top, bottom, and sides of the

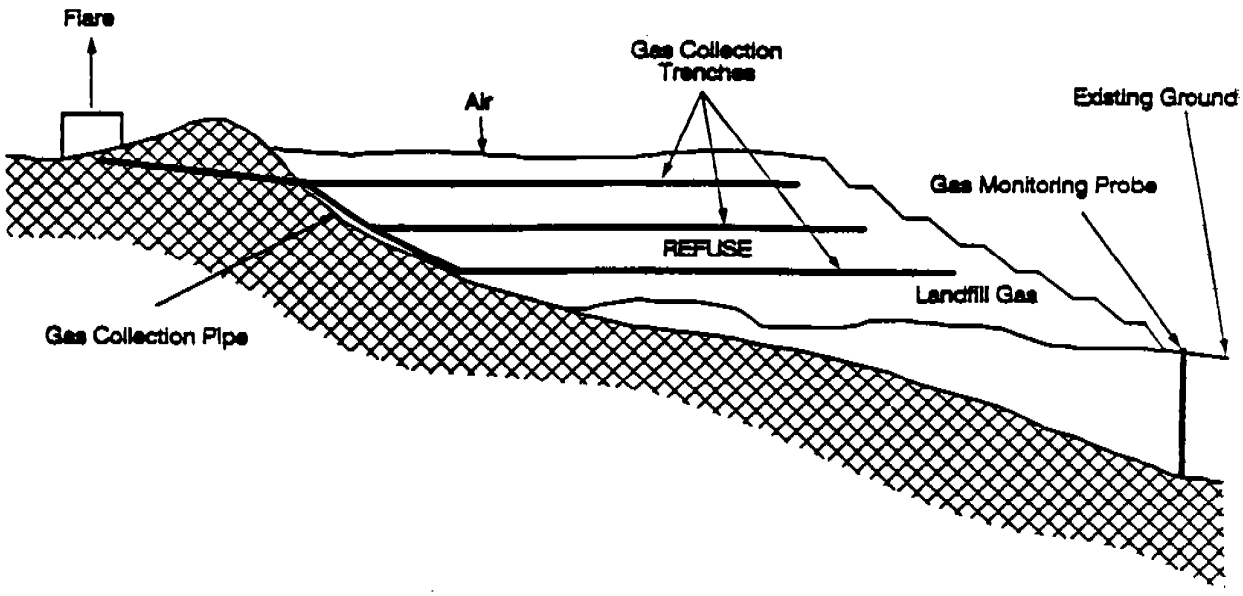


Figure 9-9. Horizontal trench collection system.

landfill. If such a collection system is proposed, two design features will need to be evaluated, the proposed well spacing and the proposed well construction. Each of these design features are addressed below.

9.2.3.1 Passive Well Spacing. The preferred methodology for determining the well spacing for passive collection systems is to use the average static landfill pressure determined from field testing. If EPA Method 2E has been performed, first determine the average static landfill pressure using all of the deep probe static pressure measurements. Second, the pressure drop across the control system should be established, based on control equipment specifications. The pressure drop across the flare (or other control device), flame arrester, and collection header piping should be considered. The expected pressure drop across the control system (usually provided in vendor specifications) should be subtracted from the landfill pressure to determine the differential pressure driving force. Using this differential pressure (between the landfill gauge pressure and the control system pressure drop), the theoretical radius of influence can be determined using Figure 9-10. Based on this theoretical radius of influence, wells should be placed throughout the landfill such that all areas of the landfill are covered and the distance between wells is no more than two times the radius of influence.

If EPA Method 2E has not been performed at the landfill, then the static landfill pressure should be determined by field measurement. The landfill should be divided into 5 equal volumes of refuse and a pressure probe should be installed near the center of each equal volume, following the probe installation procedures outlined in Section 3.3.1 of EPA Method 2E. A differential pressure gauge should be used to measure the gauge pressure at each pressure probe every 8 hours for 3 days. All 120 of these pressure measurements should be averaged to determine the static landfill pressure. This static landfill pressure should be used the same as Method 2E results (discussed above). The expected control system pressure drop (including the flare tip, flame arrester, collection header) is to be subtracted from the static landfill pressure to determine the differential pressure driving force. This differential pressure can then be used in conjunction with Figure 9-10 to determine the theoretical radius of

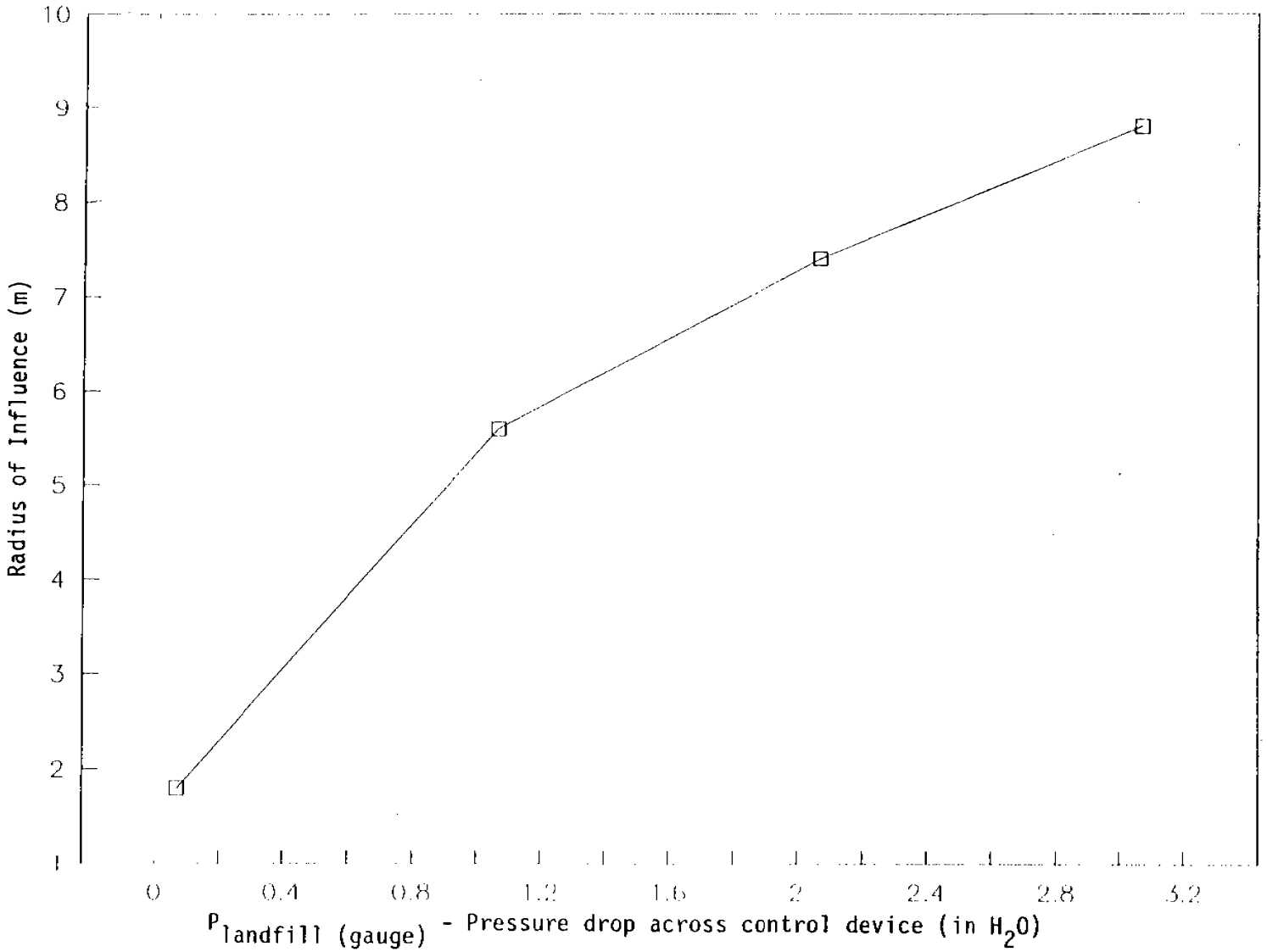


Figure 9-10. Estimated radius of influence for a passive system well as a function of the collection/control system pressure drop.

influence. Wells should be placed throughout the landfill such that all areas of the landfill are covered and the distance between wells is no more than two times the radius of influence.

9.2.3.2 Passive Well Construction. The passive extraction well is to be constructed of polyvinyl chloride (PVC) or high density polyethylene (HDPE) pipe, at least 4 inches in diameter. The well should extend from the landfill surface to at least 75 percent of the landfill depth. It is recommended that the bottom two thirds of the pipe be perforated with 1/2 inch diameter holes spaced at 90 degrees every 6 inches. The pipe should be placed in the center of a 2 ft diameter bore and backfilled with gravel to a level 1 ft above the perforated section. The remainder of the hole should be backfilled with a cover or backfilling material.

The well construction for passive systems is much less critical than active systems. This is primarily because the collection well is under positive pressure and air infiltration is not a concern. Additionally, elaborate well head assemblies are not required since monitoring and adjustment is not necessary. However, it is important that a good seal be provided around the passive well in order to maintain the integrity of the synthetic liner and maximize containment. Therefore, it is recommended that a boot type seal, flange type seal, concrete mooring or other sealing technique be used at each well location to maintain integrity of the landfill cap.

9.3 COLLECTION SYSTEM OPERATING GUIDELINES

Active landfill gas collection systems should be periodically monitored and adjusted to: (1) maximize landfill gas collection, and (2) ensure that air infiltration into the system does not exceed safe levels. Additionally, due to the inconsistency typically found within landfills, it may be necessary to install additional wells in certain areas of high gas generation.

To insure effective collection of landfill gas, the pressure and air content should be measured at each well head (vertical collection systems) or common header leg (horizontal collection systems) at least once every month. If the measured pressure at the well head is positive, then the flow from that well or set of trenches should be increased by opening the valve.

Infiltration of too much air into a landfill may cause a fire or explosion hazard. Therefore, EPA has determined that the N_2 concentration (as a surrogate for air concentration) in the collected gas should be maintained under 1 percent by volume. If the N_2 concentration exceeds 1 percent, the valve at the well head assembly should be adjusted to decrease the flow from that well, thus decreasing the level of air infiltration. In cases where the well or leg pressure is positive and the flow cannot be increased due to the exceedance of the N_2 concentration limit, additional extraction wells should be installed and added to the collection system.

In all types of collection systems with header piping, condensation of water and organics is expected to occur as a result of cooler temperatures above the surface of the landfill. This condensate is generally collected, treated for pH, and routed to a water treatment facility or discharged under NPDES permit or otherwise handled according to RCRA Subtitle D and/or Subtitle C requirements.

9.4 DESIGN AND OPERATING GUIDELINES FOR CONTROL SYSTEMS

All collected landfill gas must be routed to a control device capable of achieving 98 percent reduction of the NMOC emissions by weight. The Agency has identified a number of control devices that can achieve the specified reduction. These include: open flares, enclosed ground flares, gas turbines, internal combustion (IC) engines, boilers, incinerators, and purification systems. Open flares that are in conformance with the design and operating requirements of 40 CFR 60.18 are assumed to yield 98 percent destruction of NMOC emissions. Enclosed combustors, however, such as enclosed ground flares, turbines, IC engines, boilers, and incinerators, require a performance test to demonstrate 98 percent destruction efficiency or an outlet NMOC concentration of 20 ppmvd at 3 percent oxygen using EPA Method 25. Purification systems, such as adsorption and absorption, do not require performance testing if all vent streams from the system are routed to an open flare or enclosed combustor that meet the specifications listed above. Control of only some portion of the vent streams would be allowed if overall 98 percent destruction in NMOC emissions is achieved.

Alternatively, the landfill owner may select any NMOC destruction device, or design and operate one of the listed devices outside the range of the parameters specified if the device can be demonstrated to achieve 98 percent destruction of NMOC emissions. EPA Method 25 should be used to determine the performance of alternative control devices.

9.5 COMPLIANCE SCHEDULE

Landfill owners/operators of all designated existing MSW landfills are required to submit a design capacity report and an initial NMOC mass emission rate estimate (Tier 1) within 90 days of the effective data of their respective approved State plan for implementing the emission and compliance guidelines. Owners and/or operators of new landfills must submit a design capacity report and an initial NMOC mass emission rate estimate (Tier 1) within 90 days of start-up (i.e., refuse acceptance). Suggested contents of the report are discussed in Section 9.1.

Landfills with design capacities less than 100,000 Mg are not required to perform further testing or reporting, unless the design capacity is changed due to the addition of new areas, increase in depth, etc. If such a change occurs, the landfill owner/operator is required to submit an amended design capacity report within 90 days of the change.

Landfills with design capacities greater than 100,000 Mg, must file an annual or periodic report of the NMOC mass emission rate (Tier 1) until the landfill closes or the rate exceeds the regulatory cutoff.

When the NMOC emission rate, calculated in Tier 1, reaches 150 Mg/yr, the owner/operator must submit either a notification of intent to install a collection system based on the specifications in Section 60.758 or a collection system design plan for review within 1 year. If the landfill owner/operator elects to perform the Tier 2 sampling in order to generate a site-specific NMOC concentration or gas generation rate to use for the calculation of the more precise NMOC emission rate, he/she must report these calculations within one year of the initial Tier 1 calculation as well.

If the NMOC emission rate calculated in Tier 2 equals or exceeds 150 Mg/yr, then either controls must be installed or the owner/operator can choose to perform Tier 3 testing; either must be done within 1 year after

agency approval of a design which has been submitted for review, which takes approximately 6 months, or within 18 months after the submittal of a notification of intent. Should the NMOC emission rate calculated in Tier 2 be below 150 Mg/yr, then the Tier 2 calculation must be repeated annually, while updating the NMOC concentration data at the specified intervals, as described in Section 9.1. If the value for the NMOC emission rate from the Tier 3 testing still equals or exceeds 150 Mg/yr then controls must be installed within one year of the Tier 3 results. If the Tier 3 emission rate calculation is below 150 Mg/yr then the Tier 3 calculation must be repeated annually, while updating the NMOC concentration data at the specified intervals, as described in Section 9.1.

The Tier 3 test will be valuable for those landfills that need to install collection systems, because, as discussed in Section 9.2, flow rates obtained may be used in designing the collection system. Additionally, the test wells can serve as collection wells, if they meet the operating criteria.

After the collection and control systems have been installed, the owner/operator has 90 days to complete and submit the initial performance test results. Also, semiannual compliance reports must be submitted in which the following would be included: (1) any period in which the value of any of the monitored operating parameters falls outside the ranges identified in the initial performance test; (2) results of all annual performance tests; (3) identification of any periods for which data were excluded from these calculations; (4) any period when air pollution control equipment malfunction occurred.

Upon closure of the landfill, a closure report must be filed. If, after closure, the landfill meets the criteria outlined in Section 9.1 for discontinuing control, the landfill owner/operator must submit a report. The report should include documentation verifying that the collection and control system has been operating according to the specifications for a minimum of 15 years and that the NMOC mass emission rate has been below 150 Mg/yr for three consecutive 90 day-periods.

The landfill owner/operator may discontinue control upon the State's verification that the above requirements have been met.

The proposed regulation would also require that certain types of records be maintained. Records of the accumulated refuse in place, collection system design (including proposed and subsequent well or trench spacing), control device vendor specifications, the initial performance test results, and monitoring parameter established during the initial performance test, must be maintained on site as long as the collection system and control devices are required to be operated.

9.6 REFERENCES

1. Y.C. McGuinn, Radian Corporation, to S.A. Thorneloe, EPA:CPB, February 22, 1989, Design of municipal solid waste landfill gas collection systems and their relative installation costs.

APPENDIX A

EVOLUTION OF THE BACKGROUND INFORMATION DOCUMENT

APPENDIX A

EVOLUTION OF THE BACKGROUND INFORMATION DOCUMENT

A.1 INTRODUCTION

The purpose of this study was to develop background information to support New Source Performance Standards (NSPS) for Municipal Solid Waste Landfills (MSW landfills). Work on this study was performed by the Radian Corporation from August 1987 to _____ 1990 under contract with the U. S. Environmental Protection Agency, Office of Air Quality Planning and Standards.

The following chronology lists the major events which have occurred during the development of background information for the MSW landfills NSPS. Major events are divided into three categories: (1) site visits, (2) meetings and briefings, (3) reports and mailings.

G.2 SITE VISITS

November 16, 1987	Site visit to Puente Hills Landfill, Whittier, CA
November 17, 1987	Site visit to Toyon Canyon Landfill Power Station, Los Angeles, CA
November 18, 1987	Site visit to Palos Verdes Landfill, Whittier, CA
November 18, 1987	Site visit to Rossman Landfill, Oregon City, OR
December 15, 1987	Site visit to Rumpke Landfill, Greensboro, NC
September 13, 1989	Site visit to Wilder's Grove Landfill, Raleigh, NC

G.2 MEETINGS AND BRIEFINGS

November 16, 1987	Meeting with representatives of the Los Angeles County Sanitation District
November 17, 1987	Meeting with representatives of the South Coast Air Quality Management District

March 21-24, 1988	Presentation at Governmental Refuse Collection and Disposal Association symposium, Houston, TX
May 17, 1988	Meeting with representatives of the Governmental Refuse Collection and Disposal Association to discuss comments on draft background information document
May 18-19, 1988	Presentation at the National Air Pollution Control Techniques Advisory Committee (NAPCTAC)
June 8, 1988	Meeting with representatives of Waste Management, Inc., to discuss comments on draft background information document
August 24, 1988	Meeting with Waste Management of North America, Inc. and the landfill Gas Committee of the Governmental Refuse Collection and Disposal Association, to discuss comments on draft background information document
October 5, 1988	Meeting with representatives of Browning-Ferris Industries to discuss status of project
January 19, 1989	Meeting with Browning-Ferris Industries to discuss responses to Section 114 letters
March 16, 1989	Meeting with Waste Management, Inc. to discuss status of project and Section 114 responses
March 20-24, 1989	Presentation of status of project at Governmental Refuse Collection and Disposal Association symposium, Monterey, CA
May 4, 1989	Presentation of status of project at National Solid Waste Management Association (NSWMA) in Chicago, IL
June 7, 1989	Presentation at the National Air Pollution Control Techniques Advisory Committee (NAPCTAC)
September 6, 1989	Meeting with representatives of Combustion Engineering to discuss comments on field test procedures

G.3 REPORTS AND MAILINGS

April 5, 1988	Mailing for NAPCTAC meeting on May 18, 1988

March 15, 1989	Mailing for public comment on the preliminary analysis of the design and costing for collection systems
July 14, 1989	Mailing for public comment on draft field test procedures and test methods

APPENDIX B

INDEX TO ENVIRONMENTAL CONSIDERATIONS

APPENDIX B

INDEX TO ENVIRONMENTAL CONSIDERATIONS

A.1 INTRODUCTION

This appendix consists of a reference system which is cross indexed with the October 21, 1974, Federal Register (30 FR 37419) containing EPA guidelines for the preparation of Environmental Impact Statements. This index can be used to identify sections of the document which contain data and information germane to any portion of the Federal Register guidelines.

The are, however, other documents and docket entries which also contain data and information, of both a policy and a technical nature, used in developing the proposed standards. This appendix specifies only the portions of this document that are relevant to the indexed items.

TABLE B-1. INDEX TO ENVIRONMENTAL CONSIDERATIONS

Agency guideline for preparing regulatory action environmental impact statements (39 FR 37419)	Location within the background information document
• Background and Summary of Regulatory Alternatives	
- Regulatory alternatives	The regulatory alternatives are summarized in Chapter 5.
- Statutory basis for proposing standards	The statutory basis for the proposed standards is summarized in Chapter 1.
- Source category and affected industries	A discussion of the source category is in Chapter 3; details of the "business/economic" nature of the industries affected are presented in Chapter 8. Affected are presented in Chapter 8.
- Emission control technologies	A discussion of emission control technologies is presented in Chapter 4.
• Environmental, Energy, and Economic Impacts of Regulatory Alternatives	
- Regulatory alternatives	Various regulatory alternatives are discussed in Chapter 5.
- Environmental impacts	The environmental impacts of various regulatory alternatives are presented in Chapter 6, Section 6.1, and 6.2.
- Energy impacts	The energy impacts of various regulatory alternatives are presented in Chapter 6, Section 6.3.
- Cost impacts	Cost impacts of various regulatory alternatives are presented in Chapter 7.
- Economic impacts	The economic impacts of various regulatory alternatives are presented in Chapter 8.

APPENDIX C
LANDFILL GAS COMPOSITION DATA

APPENDIX C

LANDFILL GAS COMPOSITION DATA

The speciated landfill gas composition data for 46 municipal solid waste landfills are presented in Table C-1. This data was obtained from Section 114 responses and South Coast Air Quality Management District Test Reports. The identity of the landfills evaluated have been withheld due to the presence of confidential business information. All of the data is reported in ppmv unless otherwise noted.

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N
CHEMICAL NAME														
ETHANE	929.5				1780		0	0		0	0	0	0	0
TOLUENE	35.53	758	49.3	244.5	60.91	0.251	19.38	77.17		3	17.2	1.45	12.7	28.22
METHYLENE CHLORIDE	0.18		174		38.82		44	14	1.8	8	0.7	0.2	35	3.25
HYDROGEN SULFIDE														
ETHYLBENZENE	36.95	428			4.2		0.25	7		0.15	1.3	0.23	0.65	4.06
XYLENE		664												
1,2 - DIMETHYL BENZENE		588												
LIMONENE		470												
TOTAL XYLENE ISOMERS	64.98				2.47		0.5	15.28		0.45	2.9	9.78	1.55	8.55
α-PINENE		446												
DICHLORODIFLUOROMETHANE	0	19			43.99		32.95	11.92		23.3	0	11.85	34.5	1.3
ETHYLESTER BUTANOIC ACID		398												
PROPANE	9.76				48.8		0	4.67		7	5.2	0	6.5	0
TETRACHLOROETHENE	0.74	77		28.5	14.93	0.177	7.1	5.63	0.1	0.9	0.3	0.23	1	2.4
VINYL CHLORIDE	9.98		0.05	48.1	6.11	1	15	10.92		11.35	1	2.7	7.7	8.43
METHYLESTER BUTANOIC ACID		305												
ETHYLESTER ACETIC ACID		282												
PROPYLESTER BUTANOIC ACID		253												
1,2 - DICHLOROETHENE	0.13	34		84.7	8.58		2.78	7.82		1.65	0	0.83	1.2	5.27
METHYL ETHYL KETONE	0				1.48		0	7.67		0	0	3.75	3.65	12
THIOBISMETHANE		210												
METHLYCYCLOHEXANE		197												
TRICHLOROETHENE	0.22	34		20.4	6.96	0.069	1.38	5.23	0.8	0.4	0.3	0.18	1.55	1.54
NONANE		167												
BENZENE	1.53	23	0.95	52.2	2.76	0.299	1.05	1.53	0.4	0.1	0.3	0.35	0.7	2.6
ETHANOL		157												

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB
CHEMICAL NAME														
ETHANE	0		268.75	0		1420	0	0			0	0	0	
TOLUENE	40		125.28	37	13	221	13.9	5.85	0.197	34.2	68.5	30	2.5	
METHYLENE CHLORIDE	127.5	0.00536	29.91	14	0.5	24.5	24.67	2	0.146666		3.45	50	2	18.39
HYDROGEN SULFIDE					700									
ETHYLBENZENE	5		35.35	4	3.4	48.1	3.73	0.7			22	3.8	0.55	
XYLENE														
1,2 - DIMETHYL BENZENE														
LIMONENE														
TOTAL XYLENE ISOMERS	12.5		70.75	12		0	4.63	1.5			67.5	12	1.3	
α -PINENE														
DICHLORODIFLUOROMETHANE	7.45		16	0	0	0	24.47	11.45			16.5	30	0.5	
ETHYLESTER BUTANOIC ACID														
PROPANE	86.5		4.26	0		18.2	1.4	11			0	68	0	
TETRACHLOROETHENE	11.95		12.63	11		8.2	2.63	0.4	0.0035	5.4	7.75	9.3	0.4	12.13
VINYL CHLORIDE	19	2	16.92	13	0.84	15.2	12.43	5.2	0.7	3.42	3	5.3	0.4	2.65
METHYLESTER BUTANOIC ACID														
ETHYLESTER ACETIC ACID														
PROPYLESTER BUTANOIC ACID														
1,2 - DICHLOROETHENE	18.5		4.55	13	6.5	0	3.93	0.5		0.016	1.35	0.9	0.25	
METHYL ETHYL KETONE	4.95		18.75	5.5		NM	5	6			57.5	15	NM	
THIOBISMETHANE														
METHLYCYCLOHEXANE														
TRICHLOROETHENE	21.5	0.00615	12.98	3.1	0.2	7.85	1.67	0.2	0.0158	4.86	4.7	3.4	0.2	1.14
NONANE														
BENZENE	1.95	0.00436	5.53	1.2	0.57	2.42	0.77	0.15	0.186666	1.48	1.5	1	0	1.04
ETHANOL														

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	CC	DD	EE	FF	GG	HH	II	JJ	KK	LL	MM	NN	OO	PP
CHEMICAL NAME														
ETHANE		0	0	0		0			0					0
TOLUENE		47.5	2.1	27.2	31.5	23.33	8.63		53	64		4.73	15	10.05
METHYLENE CHLORIDE	82	9.25	3	0	20	0.33			0	54.9	18.4		32	17
HYDROGEN SULFIDE										11	47.9			
ETHYLBENZENE		10.9	0.2	2.73	5.7	5.27			4.6	1.7			2.2	0.3
XYLENE													3.7	
1,2 - DIMETHYL BENZENE														
LIMONENE														
TOTAL XYLENE ISOMERS		37.5	0.45	5.57	10	13.33			12					0.75
α -PINENE														
DICHLORODIFLUOROMETHANE		8.85	14.25	8.9	11.75	13.27			19	0	7.3			37.5
ETHYLESTER BUTANOIC ACID														
PROPANE		0	6.5	0.63		0			0					36.5
TETRACHLOROETHENE		12.25	0.25	1.53	4.6	3.7			3.8		7.5	0.012	1	0.95
VINYL CHLORIDE	6.7	7.6	1.95	14.4	2.05	4.93	18.73		0	4.5	7.7	3.43		3.25
METHYLESTER BUTANOIC ACID														
ETHYLESTER ACETIC ACID														
PROPYLESTER BUTANOIC ACID														
1,2 - DICHLOROETHENE		5.45	0.3	2.87	6.2	6.23			8.8	3.8	0	0.097	1.2	0.9
METHYL ETHYL KETONE		11	NM	6.33	5	31.33			21					4.7
THIOBISMETHANE														
METHLYCYCLOHEXANE													2.4	
TRICHLOROETHENE		3.75	0.15	0.5	3.25	1.63	0.76	9.47	1.81	1.2	3.9	0.025	2.4	0.45
NONANE														
BENZENE	4	0.65	0	0.83	1	0.57	0.916	32.3	0.6	0.77		2.84	1.2	0.2
ETHANOL														

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	QQ	RR	SS	TT
CHEMICAL NAME				
ETHANE			930	1240
TOLUENE	8.65	4.91	123	51
METHYLENE CHLORIDE			1.48	50.95
HYDROGEN SULFIDE				
ETHYLBENZENE			23.4	7.22
XYLENE				
1,2 - DIMETHYL BENZENE				
LIMONENE				
TOTAL XYLENE ISOMERS			70.9	22.8
∝-PINENE				
DICHLORODIFLUOROMETHANE			0	0.19
ETHYLESTER BUTANOIC ACID				
PROPANE			13.1	25.3
TETRACHLOROETHENE	0.3017	0.441	6.82	64.95
VINYL CHLORIDE	14.28	2.57	5.61	3.83
METHYLESTER BUTANOIC ACID				
ETHYLESTER ACETIC ACID				
PROPYLESTER BUTANOIC ACID				
1,2 - DICHLOROETHENE	0.1638	0.28	0.11	1.3
METHYL ETHYL KETONE				
THIOBISMETHANE				
METHLYCYCLOHEXANE				
TRICHLOROETHENE	0.309	0.748	2.02	7.8
NONANE				
BENZENE	0.595	2.57	2.65	4.55
ETHANOL				

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N
CHEMICAL NAME														
ACETONE	0				1.84		2.25	4.5		0	0	0	2.5	2.25
2 - BUTANOL		152												
OCTANE		152												
PENTANE	0.58				11.1		0	3.83		0.5	1.2	0	9	0
HEXANE	2.49				20.82		0	4.17		3	2.4	0	10	0
METHYLESTER ACETIC ACID		136												
1 - METHOXY - 2 - METHYL PROPANE		136												
2 - BUTANONE		129												
1,1 - DICHLOROETHANE	0.3				11.85		11.18	5.63		1.75	0.6	0.05	0	0.85
1 - BUTANOL		100												
BUTANE	0				18.76		0	0.83		1	1	0	5	0
4 - METHYL - 2 - PENTANONE		89												
2 - METHYL PROPANE		84												
1 - METHYLETHYLESTER BUTANOIC ACID		69												
2 - METHYL, METHYLESTER PROPANOIC ACID		69												
CARBON TETRACHLORIDE	0			0.065	0	0.0026	0	0		0	0	0.05	0	0
CHLOROETHANE	0.43				3.25		9.2	2.33		1.6	0	0.5	8.25	0.2
1,1,3 TRIMETHYL CYCLOHEXANE		57												
2 - METHYL - 1 - PROPANOL		51												
1,2 - DICHLOROETHANE	0.02			30.1	0.02	0.447	0.78	0	0.05	0	0	0	0	0.55
TRICHLOROFLUOROMETHANE	0.66	0	0	0	1.35	0	1.08	1.3	0	2.35	0.7	0.73	7.9	0.48
CHLOROMETHANE	1.12				0.9		0.28	0.18		1.25	0	0	6.1	0.1
2,5 DIMETHYL FURAN		41												
2 - METHYL FURAN		40												
CHLORODIFLUOROMETHANE	0.97				12.58		0	0.77		3.85	0	0	3	0
PROPENE		36												

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB
CHEMICAL NAME														
ACETONE	12		20	1		0	5.33	8.5			32	14	NM	
2 - BUTANOL														
OCTANE														
PENTANE	3.25		0.39	0		0	46.53	0.5			0	45	0	
HEXANE	6.5		6.34	0		13.4	7.13	0			0	25	0	
METHYLESTER ACETIC ACID														
1 - METHOXY - 2 - METHYL PROPANE														
2 - BUTANONE														
1,1 - DICHLOROETHANE	19.5		11.87	2.6	0.053	1.21	6.33	0.45	10		0	7.9	0.1	
1 - BUTANOL														
BUTANE	16.5		0	0		0	6.07	1.5			0	32	0	
4 - METHYL - 2 - PENTANONE														
2 - METHYL PROPANE														
1 - METHYLETHYLESTER BUTANOIC ACID														
2 - METHYL, METHYLESTER PROPANOIC ACID														
CARBON TETRACHLORIDE	0	0.0134	0	0	0	0	0	0	0.0001	0.009	0	0	0	
CHLOROETHANE	1.35		2	4.9	0.026	0.76	7.33	0			0.5	3.7	0	
1,1,3 TRIMETHYL CYCLOHEXANE														
2 - METHYL - 1 - PROPANOL														
1,2 - DICHLOROETHANE	0.45		0	0	0	0	0	0	10	0.176	0	0.1	0	
TRICHLOROFLUOROMETHANE	2.85	0	0.06	2.1	0	0.77	0.5	0.45	0	0	0.2	1.1	0	0
CHLOROMETHANE	0.6		0.7	1.4	0.21	7.19	1.33	1.2			0	3.6	0	
2,5 DIMETHYL FURAN														
2 - METHYL FURAN														
CHLORODIFLUOROMETHANE	0		0	0		0	0	1.9			0	0	0.1	
PROPENE														

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	CC	DD	EE	FF	GG	HH	II	JJ	KK	LL	MM	NN	OO	PP
CHEMICAL NAME														
ACETONE		6.5	0	8		19.33			7					7.5
2 - BUTANOL														
OCTANE														
PENTANE		0	1	1.1		0			0					18
HEXANE		0	1.5	3.83		0			1					7
METHYLESTER ACETIC ACID														
1 - METHOXY - 2 - METHYL PROPANE														
2 - BUTANONE														
1,1 - DICHLOROETHANE		2.75	0	0.1	2.3	0.4	0.31		0	1.1	0		2.4	4.5
1 - BUTANOL														
BUTANE		0	2.5	1.13		0			0					9.5
4 - METHYL - 2 - PENTANONE														
2 - METHYL PROPANE														
1 - METHYLETHYLESTER BUTANOIC ACID														
2 - METHYL, METHYLESTER PROPANOIC ACID														
CARBON TETRACHLORIDE		0	0	0		0		68.3	0	0		0.00051		0
CHLOROETHANE		1.45	0.6	4.43	3.65	0			0	0.47				0.85
1,1,3 TRIMETHYL CYCLOHEXANE														
2 - METHYL - 1 - PROPANOL														
1,2 - DICHLOROETHANE		0	0.5	0	1.8				1.9	0.14	0.7	0.122		0
TRICHLOROFLUOROMETHANE	0	3.25	1.05	0.1	0.6	0.67	0	0	0	0.96	0.8	0	0.7	11.9
CHLOROMETHANE		0	0.2	0	0.9	0			0	0.09			2.2	0.24
2,5 DIMETHYL FURAN														
2 - METHYL FURAN														
CHLORODIFLUOROMETHANE		0	1.2	0		0			1		4.8			0.25
PROPENE														

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	QQ	RR	SS	TT
CHEMICAL NAME				
ACETONE			0	0
2 - BUTANOL				
OCTANE				
PENTANE			3.96	0.67
HEXANE			6.06	17.96
METHYLESTER ACETIC ACID				
1 - METHOXY - 2 - METHYL PROPANE				
2 - BUTANONE				
1,1 - DICHLOROETHANE			0.71	8.95
1 - BUTANOL				
BUTANE			0	0
4 - METHYL - 2 - PENTANONE				
2 - METHYL PROPANE				
1 - METHYLETHYLESTER BUTANOIC ACID				
2 - METHYL, METHYLESTER PROPANOIC ACID				
CARBON TETRACHLORIDE	0.00063	0.0007	0	0
CHLOROETHANE			0.11	0.95
1,1,3 TRIMETHYL CYCLOHEXANE				
2 - METHYL - 1 - PROPANOL				
1,2 - DICHLOROETHANE	0.056	0.1635	0	0.18
TRICHLOROFLUOROMETHANE	0	0	0.47	0.63
CHLOROMETHANE			1.34	10.22
2,5 DIMETHYL FURAN				
2 - METHYL FURAN				
CHLORODIFLUOROMETHANE			1.33	4.79
PROPENE				

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N
CHEMICAL NAME														
METHYL ISOBUTYL KETONE	0				0		0	2.5		0	0	0.45	0	0.5
ETHYL MERCAPTAN														
DICHLOROFLUOROMETHANE	0.36				5.01		NM	0		0	0	NM	NM	NM
1,1,1 - TRICHLOROETHANE	0.03			5.5	0.48	0.193	0.6	0.37		0.2	0.6	0.03	1.35	0
TETRAHYDROFURAN		30												
ETHYLESTER PROPANOIC ACID		26												
BROMODICHLOROMETHANE	0.22				0.12		0	0		0	0	0	0	0
ETHYL ACETATE														
3 - METHYLHEXANE		20												
C10H16 UNSATURATED HYDROCARBON														
METHYLPROPANE														
CHLOROBENZENE	0.15				0		0	0		0	0	0.05	0	0.2
ACRYLONITRILE	0				0.8		0	0		0	0	0	0	0
METHYLETHYLPROPANOATE														
1,1 - DICHLOROETHENE	0.08				0.23		0.43	0.18	3.1	0.15	0	0	0.1	0.05
METHYL MERCAPTAN														
1,2 - DICHLOROPROPANE	0.06				0.02		0	0		0	0	0	0	0
i - PROPYL MERCAPTAN														
CHLOROFORM	1.56			0.94	0	0.049	0	0		0	0	0	0	0
1,1,2,2 - TETRACHLOROETHANE	0				0		0	0		0	0	0.01	0	0
1,1,2,2 - TETRACHLOROETHENE														
2 - CHLOROETHYLVINYL ETHER	0				0		0	0		0	0	2.25	0	0
t - BUTYL MERCAPTAN														
DIMETHYL SULFIDE														

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB
CHEMICAL NAME														
METHYL ISOBUTYL KETONE	1.15		5	1		NM	1	0			11.5	1.2	NM	
ETHYL MERCAPTAN					11									
DICHLOROFLUOROMETHANE	NM		0	NM		NM	NM	NM			NM	NM	NM	
1,1,1 - TRICHLOROETHANE	4.2		0.5	1.3	0	1.24	0.47	0	0.00024	9	0	1.9	0	
TETRAHYDROFURAN														
ETHYLESTER PROPANOIC ACID														
BROMODICHLOROMETHANE	0		2.48	0	0	7.85	0	0	0.001		0	0	0	
ETHYL ACETATE														
3 - METHYLHEXANE														
C10H16 UNSATURATED HYDROCARBON														
METHYLPROPANE														
CHLOROBENZENE	0		10	0	0	0	0	0			0	0	0	
ACRYLONITRILE	0		0	0		7.4	0	0			0	0	0	
METHYLETHYLPROPANOATE														
1,1 - DICHLOROETHENE	0.65		0.75	0	0.04	0	0.13	0			0	0.2	0	0.07
METHYL MERCAPTAN					3.3									
1,2 - DICHLOROPROPANE	1.8		0.5	0	0	0	0.27	0			0	0	0	
i - PROPYL MERCAPTAN					2.1									
CHLOROFORM	0		0	0	0	0	0	0	0.001	0.234	0	0	0	
1,1,2,2 - TETRACHLOROETHANE	0		0	0	0	0	0	0			2.35	0.2	0	
1,1,2,2 - TETRACHLOROETHENE					0.05									
2 - CHLOROETHYLVINYL ETHER	0		0	0	0	0	0	0			0	0	0	
t - BUTYL MERCAPTAN					0.28									
DIMETHYL SULFIDE					0.1									

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	CC	DD	EE	FF	GG	HH	II	JJ	KK	LL	MM	NN	OO	PP
CHEMICAL NAME														
METHYL ISOBUTYL KETONE		4	NM	3.33		3.33			1					0
ETHYL MERCAPTAN										1	23.8			
DICHLOROFLUOROMETHANE		NM	0	NM	NM	NM			NM		1.7			NM
1,1,1 - TRICHLOROETHANE		0.4	0	0	0.25	0	0.016		0	0.37		0.019	0.7	1.15
TETRAHYDROFURAN														
ETHYLESTER PROPANOIC ACID														
BROMODICHLOROMETHANE		0	0	0		0			0	0				0
ETHYL ACETATE													20	
3 - METHYLHEXANE														
C10H16 UNSATURATED HYDROCARBON													15	
METHYLPROPANE													12	
CHLOROBENZENE		0	0	0		0.1			0	0	0.1			0
ACRYLONITRILE		0	0	0		0			0					0
METHYLETHYLPROPANOATE													7.3	
1,1 - DICHLOROETHENE		0.2	0	0	0.1	0			0	0.064	0			0.2
METHYL MERCAPTAN										1	1.3			
1,2 - DICHLOROPROPANE		0.35	0	0		0			0	0.03				0
i - PROPYL MERCAPTAN										1				
CHLOROFORM		0	0	0		0			0	0	0	0.0016		0
1,1,2,2 - TETRACHLOROETHANE		0	0	0		0			0	0				0
1,1,2,2 - TETRACHLOROETHENE										2.6				
2 - CHLOROETHYLVINYL ETHER		0	0	0		0			0	0				0
t - BUTYL MERCAPTAN										1				
DIMETHYL SULFIDE										1				
DICHLOROTETRAFLUOROETHANE											1.1			
DIMETHYL DISULFIDE										1				

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	QQ	RR	SS	TT
CHEMICAL NAME				
METHYL ISOBUTYL KETONE				
ETHYL MERCAPTAN				
DICHLOROFLUOROMETHANE			0.48	26.11
1,1,1 - TRICHLOROETHANE	0.0152	0.023	0.16	0.77
TETRAHYDROFURAN				
ETHYLESTER PROPANOIC ACID				
BROMODICHLOROMETHANE			2.02	7.8
ETHYL ACETATE				
3 - METHYLHEXANE				
C10H16 UNSATURATED HYDROCARBON				
METHYLPROPANE				
CHLOROBENZENE			0.43	0
ACRYLONITRILE			0	0
METHYLETHYLPROPANOATE				
1,1 - DICHLOROETHENE			0	0.49
METHYL MERCAPTAN				
1,2 - DICHLOROPROPANE			0.22	0.12
i - PROPYL MERCAPTAN				
CHLOROFORM	0.00278	0.0058	0	0
1,1,2,2 - TETRACHLOROETHANE			0.11	0
1,1,2,2 - TETRACHLOROETHENE				
2 - CHLOROETHYLVINYL ETHER			0	0
t - BUTYL MERCAPTAN				
DIMETHYL SULFIDE				

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	A	B	C	D	E	F	G	H	I	J	K	L	M
CHEMICAL NAME													
DICHLOROTETRAFLUOROETHANE													
DIMETHYL DISULFIDE													
CARBONYL SULFIDE													
1,1,2-TRICHLORO 1,2,2-TRIFLUOROETHANE													
METHYL ETHYL SULFIDE													
1,1,2 - TRICHLOROETHANE	0				0		0	0		0	0	0	0
1,3 - BROMOCHLOROPROPANE													
1,2 - DIBROMOETHANE													
C-1,3 - DICHLOROPROPENE													
t-1,3 - DICHLOROPROPENE													
ACROLEIN	0				0		0	NM		0	0	0	0
1,4 -DICHLOROBENZENE	0				0		0	0		0	0	0	0
BROMOFORM	0				0		0	0		0	0	0	0
1,3 - DICHLOROPROPANE	0				0		0	0		0	0	0	0
1,2 - DICHLOROBENZENE	0				0		0	0		0	0	0	0
1,3 - DICHLORBENZENE	0				0		0	0		0	0	0	0
DIBROMOCHLOROMETHANE	0				0		0	0		0	0	0	0
BROMOMETHANE	0				0		0	0		0	0	0	0

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
CHEMICAL NAME														
DICHLOROTETRAFLUOROETHANE														
DIMETHYL DISULFIDE						0.1								
CARBONYL SULFIDE														
1,1,2-TRICHLORO 1,2,2-TRIFLUOROETHANE														
METHYL ETHYL SULFIDE						0.32								
1,1,2 - TRICHLOROETHANE	0	0.1		0	0	0	0	0	0			0	0	0
1,3 - BROMOCHLOROPROPANE										0.005				
1,2 - DIBROMOETHANE										0.0005				
C-1,3 - DICHLOROPROPENE						0								
t-1,3 - DICHLOROPROPENE						0								
ACROLEIN	0	0		NM	0		NM	0	0			0	0	NM
1,4 -DICHLOROBENZENE	0	0		0	0	0	0	0	0			0	0	0
BROMOFORM	0	0		0	0	0	0	0	0			0	0	0
1,3 - DICHLOROPROPANE	0	0		0	0		0	0	0			0	0	0
1,2 - DICHLOROBENZENE	0	0		0	0	0	0	0	0			0	0	0
1,3 - DICHLORBENZENE	0	0		0	0	0	0	0	0			0	0	0
DIBROMOCHLOROMETHANE	0	0		0	0	0	0	0	0			0	0	0
BROMOMETHANE	0	0		0	0	0	0	0	0			0	0	0

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	BB	CC	DD	EE	FF	GG	HH	II	JJ	KK	LL	MM	NN	OO
CHEMICAL NAME														
DICHLOROTETRAFLUOROETHANE												1.1		
DIMETHYL DISULFIDE											1			
CARBONYL SULFIDE											1			
1,1,2-TRICHLORO 1,2,2-TRIFLUOROETHANE												0.5		
METHYL ETHYL SULFIDE														
1,1,2 - TRICHLOROETHANE			0	0	0		0			0	0			
1,3 - BROMOCHLOROPROPANE														
1,2 - DIBROMOETHANE							0							
C-1,3 - DICHLOROPROPENE											0			
t-1,3 - DICHLOROPROPENE											0			
ACROLEIN			0	NM	0		0			0				
1,4 -DICHLOROBENZENE			0	0	0		0			0	0			
BROMOFORM			0	0	0		0			0	0			
1,3 - DICHLOROPROPANE			0	0	0		0			0				
1,2 - DICHLOROBENZENE			0	0	0		0			0	0	0		
1,3 - DICHLORBENZENE			0	0	0		0			0	0	0		
DIBROMOCHLOROMETHANE			0	0	0		0			0	0			
BROMOMETHANE			0	0	0		0			0	0			

TABLE C-1. SPECIATED NMOC COMPOSITION

LANDFILL ID	QQ	RR	SS	TT
CHEMICAL NAME				
DICHLOROTETRAFLUOROETHANE				
DIMETHYL DISULFIDE				
CARBONYL SULFIDE				
1,1,2-TRICHLORO 1,2,2-TRIFLUOROETHANE				
METHYL ETHYL SULFIDE				
1,1,2 - TRICHLOROETHANE			0	0
1,3 - BROMOCHLOROPROPANE				
1,2 - DIBROMOETHANE				
C-1,3 - DICHLOROPROPENE				
t-1,3 - DICHLOROPROPENE				
ACROLEIN			NM	NM
1,4 -DICHLOROBENZENE			0	0
BROMOFORM			0	0
1,3 - DICHLOROPROPANE			0	0
1,2 - DICHLOROBENZENE			0	0
1,3 - DICHLORBENZENE			0	0
DIBROMOCHLOROMETHANE			0	0
BROMOMETHANE			0	0

APPENDIX D: GAS GENERATION RATE MODELING

This appendix provides samples calculations for estimating the landfill air emission rate using the Scholl Canyon model, as well as, a brief discussion of alternative methods. Section D.1 contains a short description of the Scholl Canyon model and sample calculations for 4 model cases. Section D.2 discusses the emission factor method, the SCAQMD method and the Municipal Waste Generation Rate method as alternative techniques for estimating nationwide landfill air emissions.

D.1 Scholl Canyon Model.

The Scholl Canyon model is a single stage, first order kinetic model. It assumes that after a negligible lag time during which anaerobic conditions are established, the gas production rate is at its peak. After the lag time, the gas production rate is assumed to decrease exponentially as the organic fraction of the landfill refuse decreases. The model equation is as follows:[1]

$$\frac{dG}{dt} = kL = kL_0 e^{-kt}$$

where,

$\frac{dG}{dt}$ = methane production rate, ft^3/lb of refuse-yr.

k = rate constant, 1/year

t = time, year

L_0 = total volume of methane ultimately to be produced, ft^3/lb of refuse

If the refuse mass is broken down into the submasses which are placed during each year of the landfill's operation, the model equation is:

$$\frac{dG}{dt} = kL = kL_0 \sum_{i=1}^{n} r_i \exp(-k_i t_i)$$

where,

r_i = fraction of total refuse mass contained in submass i

t_i = time from placement of submass i to point in time at which composite production rate is desired, yr

k_i = gas production rate constant for submass i, 1/year

The rate constant , k, can be calculated if the time and quantity of each refuse submass placement, and the gas flowrate at a given time are known. Once k is calculated from the equation, the methane generation rate at any time can be estimated. Figure D-1 depicts the Scholl Canyon model simulation for two different values of L_0.[2]

D.1.1 Sample Calculations Using Scholl Canyon Model

This section discusses how to use the Scholl Canyon Model to estimate gas generation for several hypothetical landfills (Case 1 through 4 below). In case 1, information on how to estimate the VOC emission rate and toxic compound emission rate is also presented. To use the model, it is necessary for the landfill owner or operator to obtain representative values of gas generation rate, nonmethane organic compound concentration, and toxic compound concentration via field testing (as discussed in Chapter 9.0).

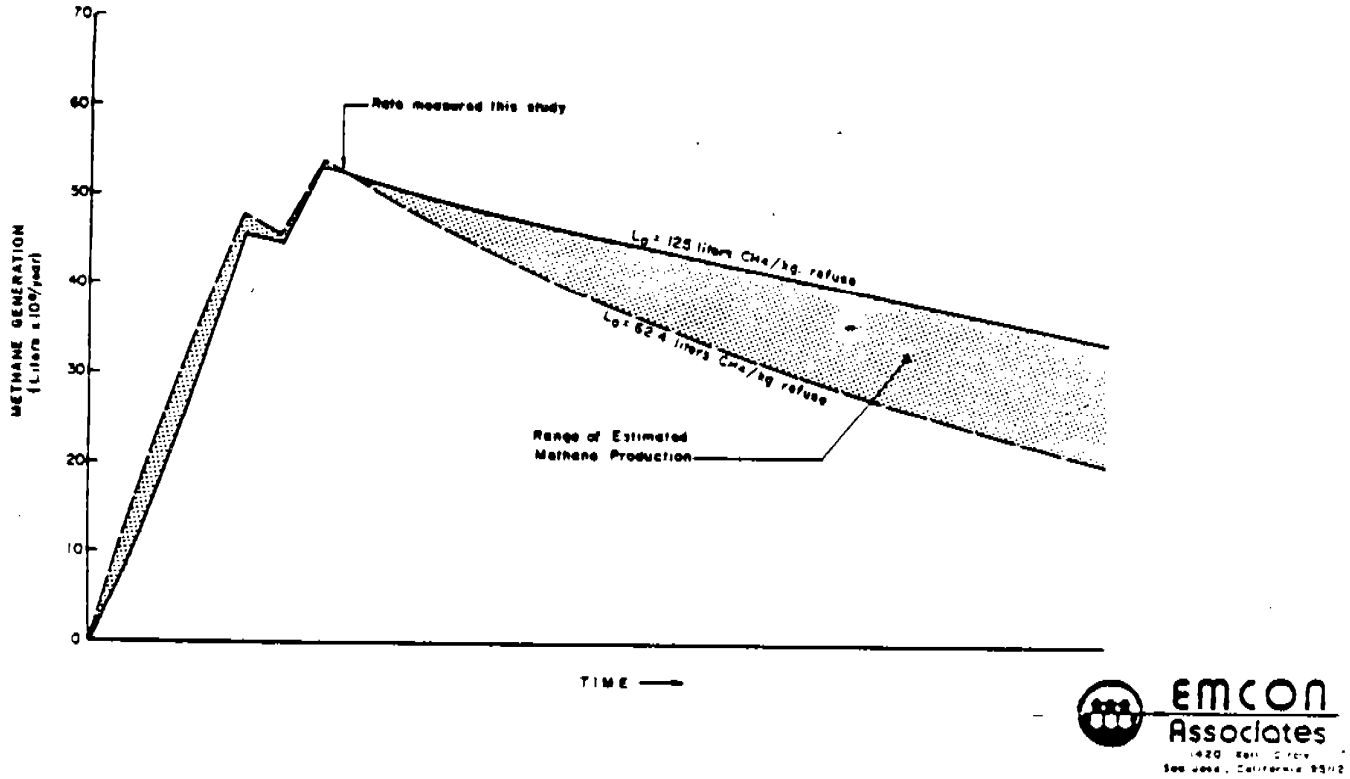


Figure D-1. Estimated methane production (Scholl Canyon Kinetic Model)

D.1.1.1 Case 1

Given: Landfill A was in operation for 15 years accepting refuse at an average rate of 133,300 Mg/yr. It closed after 15 years of operation with 2×10^6 Mg of refuse in place (RIP). Test well data conducted one year after closure (16 years after initial placement of refuse), indicated that Landfill A is capable of producing 0.0715 ft^3/lb-yr of methane gas. Test well data also showed that the average concentration of nonmethane organic compounds is 1500 ppm and the concentration of toxic compounds is as follows: benzene (120 ppm), methylene chloride (50 ppm), vinyl chloride (100 ppm).

Calculate: Kinetic constant (k), methane generation rate as a function of time, emission rate of VOC, and emission rate of toxic compounds.

1. First, reduce test well data to the actual recoverable methane production rate.

Total recoverable methane gas rate = (test well flowrate)(refuse in place)

$$\text{Total recoverable methane gas rate} = (0.0715)\ (2 \times 10^{12}\ \text{g})\ \frac{\text{lb}}{454\ \text{g}}$$

$$= 315 \times 10^6\ ft^3\ \text{methane/yr.}$$

2. Calculate the fraction of submass i, r_i, by treating yearly accumulation as the mass of submass i.

$$r_i = \frac{133,300}{2 \times 10^6} = 0.0667$$

3. Calculate the kinetic constant, k, using the recoverable methane gas rate calculated in Step 1 and t of 16 years.

$$\left.\frac{dG}{dt}\right|_{t = 16} = k L_o M_t \sum_{t_i = 1}^{t_i = 15} \exp\left[-k (t_i + t_c)\right]$$

where, t_c = time after closure (= 1 year)

M_t = amount of refuse accumulated at time t

$t_i + t_c$ = age of submass i

[Note that the actual age of the submass i is corrected by adding the time after closure.]

Assuming L_o of 100 liter CH_4/Kg refuse or 3.53×10^3 ft^3 CH_4/Mg refuse,

$$315 \times 10^6 \frac{ft^3\ CH_4}{yr} = k \left(3.53 \times 10^3 \frac{ft^3\ CH_4}{Mg\ refuse}\right) (2 \times 10^6\ Mg\ refuse)$$

$$X \sum_{i = 1}^{i = 15} (0.0667) \exp\left[-k (t + 1)\right]$$

$$0.669 = k \sum_{i = 1}^{i = 15} \exp\left[-k (t_i + 1)\right]$$

$$= k \left\{\exp(-2k) + \exp(-3k) + \ldots \exp(-16k)\right\}$$

Solving for k by trial and error procedures, $k \doteq 0.1$ 1/yr.

4. Express the model equation with calculated k.

$$\frac{dG}{dt} = k\, L_o\, M_t \sum_{i=1}^{i=15} r_i \exp\left[-k\,(t_i + t_c)\right]$$

$$= (0.1)\,(3.53 \times 10^3)\,(2 \times 10^6)\,(0.0667) \sum_{t_i=1}^{t_i=15} \exp\left[-0.1\,(t_i + t_c)\right]$$

$$= 4.707 \times 10^7 \sum_{t_i=1}^{t_i=15} \exp\left[-0.1\,(t_i + t_c)\right] \text{ in } ft^3 \frac{CH_4}{yr} \qquad (1)$$

5. The future methane gas generation rate now can be calculated by changing t_c. For example, the methane gas generation 5 years after closure may be calculated by setting $t_c = 5$ in Equation (1).

6. The methane gas generation rate before closure can be calculated by modifying the equation (1).

$$\frac{dG}{dt}\text{ (before closure)} = (k\, L_o\, M_n) \sum_{t_i=1}^{t_i=n} \frac{\exp\,(-k\, t_i)}{(n)} \qquad (2)$$

where, M_n = amount of refuse accumulated over n years.

n = number of years since the initial placement of refuse but before closure

$$\frac{dG}{dt}\text{ (before closure)} = \frac{(0.1)(3.53 \times 10^3)}{n} M_n \sum_{t_i=1}^{t_i=n} \exp\,(-0.1 t_i)$$

Figure D-2 shows the methane generation rate as a function of time for Landfill A.

7. The VOC emission rate can be calculated by inputting the nonmethane organic compound (i.e. VOC) concentration measured during field testing. The example below represents VOC emissions in year 16 of the landfill.

   - The methane generation rate (315×10^6 ft^3/yr) should be multiplied by 2 to calculate total gas generation. This step assumes that landfill gas is 50 percent methane.

     o 315×10^6 ft^3/yr $\times$ 2 = 630×10^6 ft^3/yr

   - Using the calculated nonmethane organic compound concentration of 1500 ppm and assuming an average VOC molecular weight of 80:

     o $$\frac{630 \times 10^6 \text{ ft}^3}{\text{yr}} \left| \frac{0.0015 \text{ VOC}}{} \right| \frac{\text{lb mol}}{359 \text{ ft}^3} \left| \frac{80 \text{ lb}}{\text{lb mol}} \right.$$

     = 210,000 lb VOC per year
     = 95 Mg VOC per year

8. The toxic compound emission rate can be calculated by inputting the concentration of each toxic compound measured during field testing. The example below represents toxic compound concentration in year 16 of the landfill.

   o $$\frac{630 \times 10^6 \text{ ft}^3}{\text{yr}} \left| \frac{0.00012 \text{ benzene}}{} \right| \frac{\text{lb mol}}{359 \text{ ft}^3} \left| \frac{78 \text{ lb}}{\text{lb mol}} \right.$$

   $$= \frac{16{,}400 \text{ lb benzene}}{\text{yr}} = 7{,}400 \frac{\text{kg}}{\text{yr}} \text{ benzene}$$

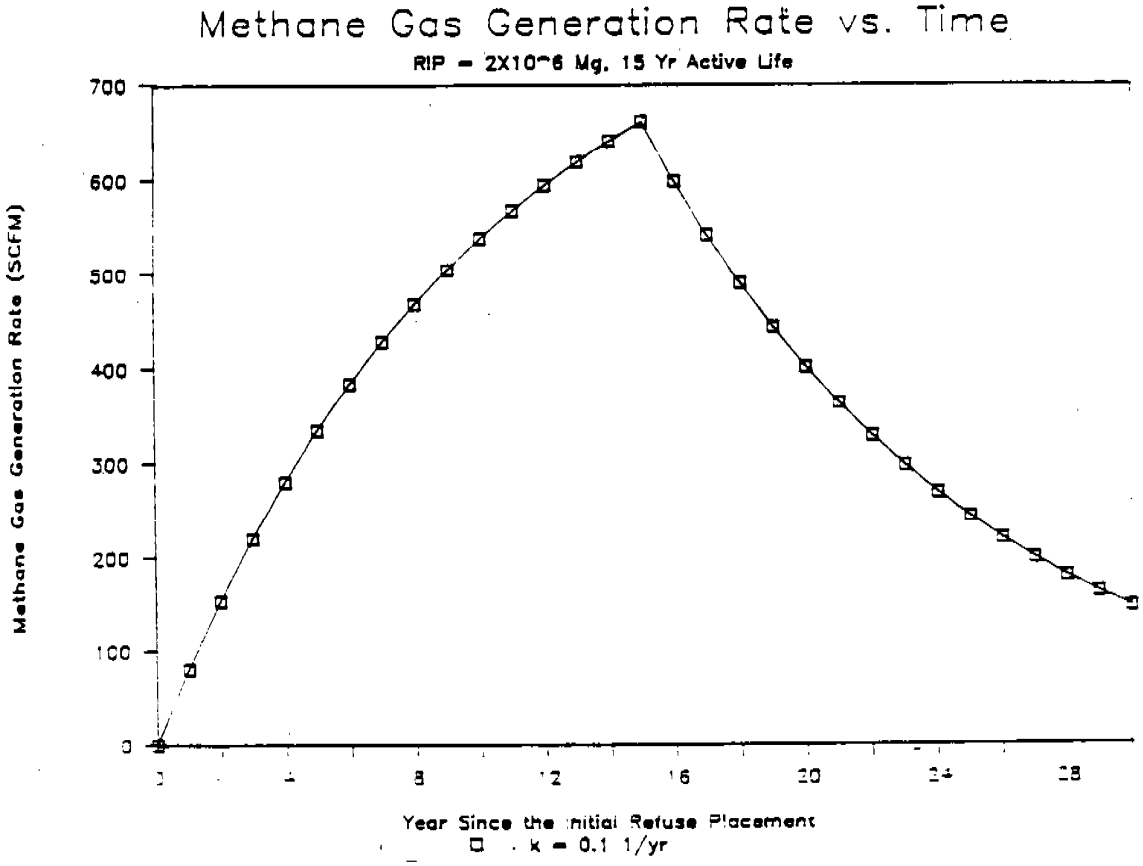


Figure D-2. Methane gas generation rate as a function of time.

- $\frac{630 \times 10^6 \text{ ft}^3}{\text{yr}} \left| \frac{0.00005 \text{ MC}}{} \right| \frac{\text{lb mol}}{359 \text{ ft}^3} \left| \frac{85 \text{ lb}}{\text{lb mol}} \right.$

  $= 7{,}450 \frac{\text{lb}}{\text{yr}} \text{ MC} = 3{,}380 \frac{\text{kg}}{\text{yr}} \text{ MC}$

- $\frac{630 \times 10^6 \text{ ft}^3}{\text{yr}} \left| \frac{0.00015 \text{ VC}}{} \right| \frac{\text{lb mol}}{359 \text{ ft}^3} \left| \frac{62 \text{ lb}}{\text{lb mol}} \right.$

  $= 16{,}300 \frac{\text{lb}}{\text{yr}}$ Vinyl Chloride $= 7{,}400 \frac{\text{kg}}{\text{yr}}$ VC

D.4.2 Case 2

Given: Landfill B was in operation for 15-years accepting refuse at an average rate of 133,300 Mg/yr. It clsoed after 15 years of operation with 2×10^6 Mg of refuse in place (RIP). Test well data conducted two years after closure (17 years after initial placement of refuse), indicated that Landfill B is capable of producting 0.061 ft^3/lb-yr of methane gas.

Calculate: Kinetic constant (k) and methane generation rate as a function of time.

1. First, reduce test well data to the actual recoverable methane production rate.

   Total recoverable methane gas rate = (test well flowrate)(refuse in place)

Total recoverable methane gas rate = $(0.061)\ (2 \times 10^{12}\ g)\ \frac{lb}{454\ g}$

$= 269 \times 10^6\ ft^3$ methane/yr.

2. Calculate the fraction of submass i, r_i, by treating yearly accumulation as the mass of submass i.

$$r_i = \frac{133,300}{2 \times 10^6} = 0.0667$$

3. Calculate the kinetic constant, k, using the recoverable methane gas rate calculated in Step 1 and t of 17 years.

$$\left.\frac{dG}{dt}\right|_{t = 17} = k\, L_o\, M_t \sum_{t_i = 1}^{t_i = 15} \exp\left[-k\,(t_i + t_c)\right]$$

where, t_c = time after closure (= 2 years)

M_t = amount of refuse accumulated at time t

$t_i + t_c$ = age of submass i

Assuming L_o of 100 liter CH_4/Kg refuse or $3.53 \times 10^3\ ft^3\ CH_4$/Mg refuse,

$$269 \times 10^6\ \frac{ft^3\ CH_4}{yr} = k\left(3.53 \times 10^3\ \frac{ft^3\ CH_4}{Mg\ refuse}\right)(2 \times 10^6\ Mg\ refuse)$$

$$\times \sum_{i = 1}^{i = 15} (0.0667) \exp\left[-k\,(t + 2)\right]$$

$$0.571 = k \sum_{i=1}^{i=15} \exp\left[-k\,(t_i + 2)\right]$$

$$= k\,\{\exp(-3k) + \exp(-4k) + \ldots \exp(-17k)\}$$

Solving for k by trial and error procedures, $k \cong 0.2$ 1/yr.

4. Express the model equation with calculated k.

$$\frac{dG}{dt} = k\,L_o\,M_t \sum_{i=1}^{i=15} r_i \exp\left[-k\,(t_i + t_c)\right]$$

$$= (0.2)\,(3.53 \times 10^3)\,(2 \times 10^6)\,(0.0667) \sum_{t_i=1}^{t_i=15} \exp\left[-0.1\,(t_i + t_c)\right]$$

$$= 9.414 \times 10^7 \sum_{t_i=-1}^{t_i=15} \exp\left[-0.2\,(t_i + t_c)\right] \text{ in ft}^3\,\frac{CH_4}{yr}$$

5. The methane gas generation rate before closure can be calculated by:

$$\frac{dG}{dt}\,(\text{before closure}) = (k\,L_o\,M_n) \sum_{t_i=1}^{t_i=n} \frac{\exp(-k\,t_i)}{(n)} \qquad (2)$$

where, M_n = amount of refuse accumulated over n years.

n = number of years since the initial placement of refuse but before closure

$$\frac{dG}{dt}\,(\text{before closure}) = \frac{(0.2)(3.53 \times 10^3)}{n}\,M_n \sum_{t_i=1}^{t_i=n} \exp(-0.2t_i)$$

Figure D-3 shows the methane generation rate as a function of time for Landfill B.

D.4.3 Case 3

Given: Landfill C was in operation for 15 years accepting refuse at an average rate of 333,300 Mg/yr. It closed after 15 years of operiaton with 5×10^6 Mg of refuse in place (RIP). Test well data conducted one year after closure (16 years after initial placement of refuse), indicated that Landfill C is capable of producing 0.0715 ft^3/lb-yr of methane gas.

Calculate: Kinetic constant (k) and methane generation rate as a function of time.

1. First, reduce test well data to the actual recoverable methane production rate.

Total recoverable methane gas rate = (test well flowrate)(refuse in place)

Total recoverable methane gas rate = $(0.0715)\ (5 \times 10^{12}\ g)\ \frac{lb}{454\ g}$

$= 790 \times 10^6\ ft^3$ methane/yr.

2. Calculate the fraction of submass i, r_i, by treating yearly accumulation as the mass of submass i.

$$r_i = \frac{333,300}{5 \times 10^6} = 0.0667$$

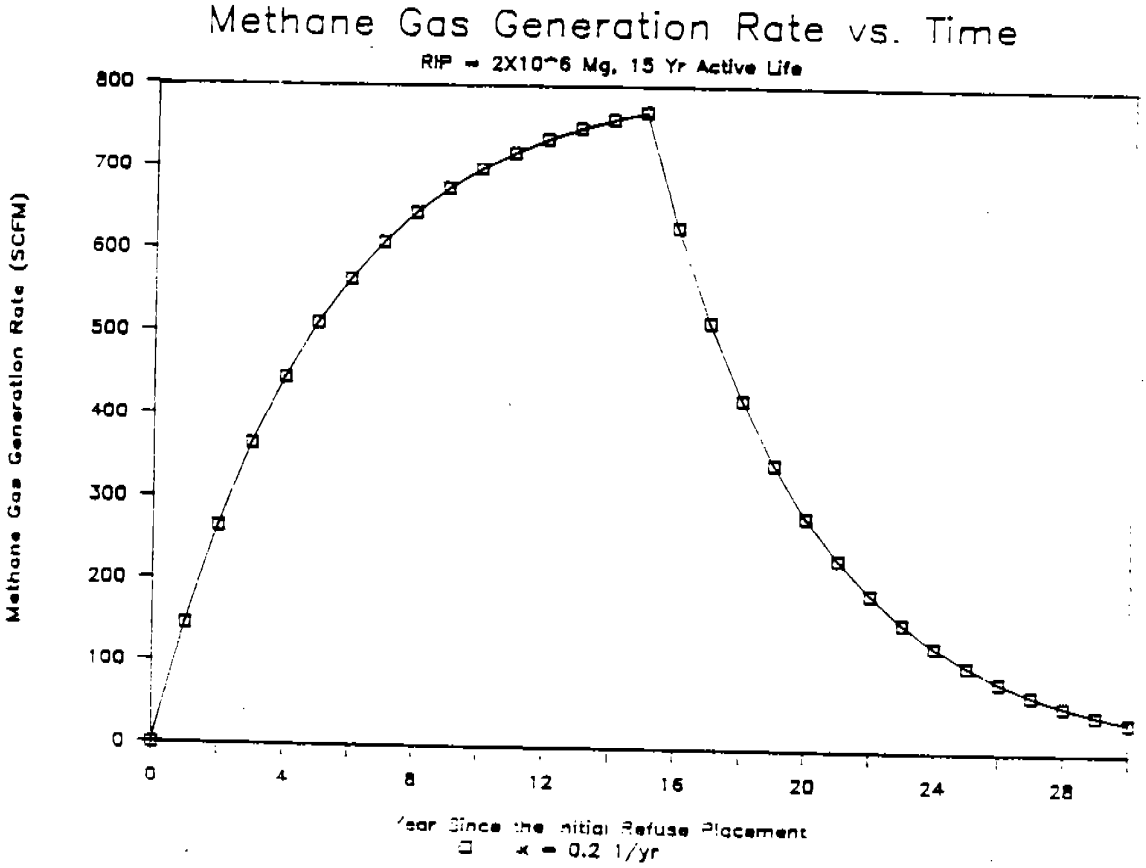


Figure D-3. Methane gas generation rate as a function of time.

3. Calculate the kinetic constant, k, using the recoverable methane gas rate calculated in Step 1 and t of 16 years.

$$\left(\frac{dG}{dt}\right)_{t = 16} = k\, L_o\, M_t \sum_{t_i = 1}^{t_i = 15} \exp\left[-k\,(t_i + t_c)\right]$$

where, t_c = time after closure (= 1 year)

M_t = amount of refuse accumulated at time t

$t_i + t_c$ = age of submass i

Assuming L_o of 100 liter CH_4/Kg refuse or 3.53×10^3 ft^3 CH_4/Mg refuse,

$$790 \times 10^6 \frac{ft^3\ CH_4}{yr} = k\left(3.53 \times 10^3 \frac{ft^3\ CH_4}{Mg\ refuse}\right)(5 \times 10^6\ Mg\ refuse)$$

$$\times \sum_{i = 1}^{i = 15} (0.0667) \exp\left[-k\,(t + 1)\right]$$

$$0.669 = k \sum_{i = 1}^{i = 15} \exp\left[-k\,(t_i + 1)\right]$$

$$= k\left\{\exp(-3k) + \exp(-4k) + \ldots \exp(-17k)\right\}$$

Solving for k by trial and error procedures, $k \cong 0.1$ 1/yr.

4. Express the model equation with calculated k.

$$\frac{dG}{dt} = k\, L_o\, M_t \sum_{i = 1}^{i = 15} r_i \exp\left[-k\,(t_i + t_c)\right]$$

$$= (0.1)\,(3.53 \times 10^3)\,(5 \times 10^6)\,(0.0667) \sum_{t_i = 1}^{t_i = 15} \exp\left[-0.1\,(t_i + t_c)\right]$$

$$= 11.77 \times 10^7 \sum_{t_i=1}^{t_i=15} \exp\left[-0.1\,(t_i + t_c)\right] \text{ in ft}^3 \frac{CH_4}{yr}$$

5. The methane gas generation rate before closure can be calculated by:

$$\frac{dG}{dt}\,(\text{before closure}) = (k\,L_o\,M_n) \sum_{t_i=1}^{t_i=n} \frac{\exp(-k\,t_i)}{(n)} \qquad (2)$$

where, M_n = amount of refuse accumulated over n years.

n = number of years since the initial placement of refuse but before closure

$$\frac{dG}{dt}\,(\text{before closure}) = \frac{(0.1)(3.53 \times 10^3)}{n} M_n \sum_{t_i=1}^{t_i=n} \exp(-0.1t_i)$$

Figure D-4 shows the methane generation rate as a function of time.

D.4.4 Case 4

Given: Landfill D was in operation for 15 years accepting refuse at an average rate of 333,300 Mg/yr. It closed after 15 years of operation with 5×10^6 Mg of refuse in place (RIP). Test well data conducted two years after closure (17 years after initial placement of refuse), indicated that Landfill D is capable of producing 0.061 ft^3/lb-yr of methane gas.

Calculate: Kinetic constant (k) and methane generation rate as a function of time.

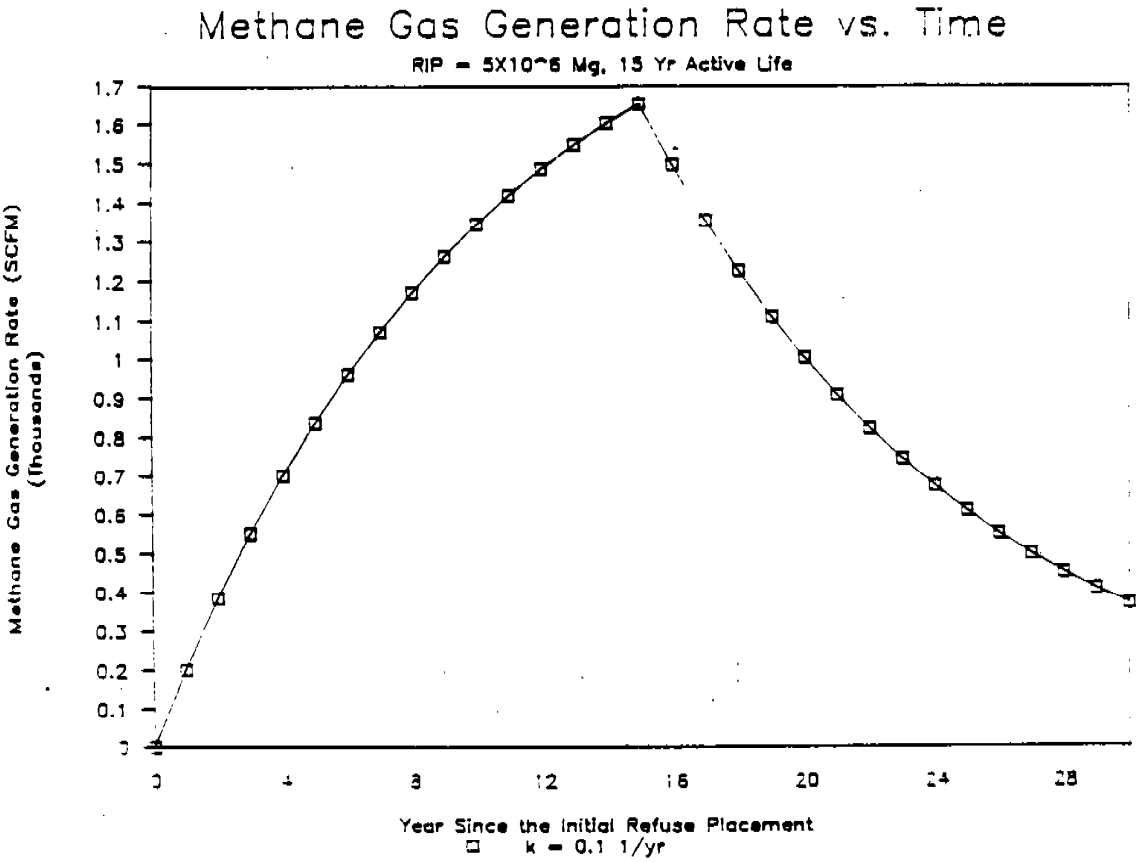


Figure D-4. Methane gas generation rate as a function of time.

1. First, reduce test well data to the actual recoverable methane production rate.

   Total recoverable methane gas rate = (test well flowrate)(refuse in place)

   $$\text{Total recoverable methane gas rate} = (0.061)\ (5 \times 10^{12}\ \text{g})\ \frac{\text{lb}}{454\ \text{g}}$$

   $$= 680 \times 10^{6}\ \text{ft}^3\ \text{methane/yr.}$$

2. Calculate the fraction of submass i, r_i, by treating yearly accumulation as the mass of submass i.

   $$r_i = \frac{333{,}300}{5 \times 10^{6}} = 0.0667$$

3. Calculate the kinetic constant, k, using the recoverable methane gas rate calculated in Step 1 and t of 17 years.

   $$\left.\frac{dG}{dt}\right|_{t = 17} = k\, L_o\, M_t \sum_{t_i = 1}^{t_i = 15} \exp\left[-k\,(t_i + t_c)\right]$$

   where, t_c = time after closure (= 2 years)

   M_t = amount of refuse accumulated at time t

   $t_i + t_c$ = age of submass i

   Assuming L_o of 100 liter CH_4/Kg refuse or 3.53×10^3 ft^3 CH_4/Mg refuse,

   $$680 \times 10^{6}\ \frac{\text{ft}^3\ \text{CH}_4}{\text{yr}} = k\ (3.53 \times 10^{3}\ \frac{\text{ft}^3\ \text{CH}_4}{\text{Mg refuse}})\ (5 \times 10^{6}\ \text{Mg refuse})$$

$$X \sum_{i=1}^{i=15} (0.0667) \exp [-k (t + 2)]$$

$$0.571 = k \sum_{i=1}^{i=15} \exp [-k (t_i + 2)]$$

$$= k \{\exp (-3k) + \exp (-4k) + \ldots \exp (-17k)\}$$

Solving for k by trial and error procedures, $k \simeq 0.2$ 1/yr.

4. Express the model equation with calculated k.

$$\frac{dG}{dt} = k L_o M_t \sum_{i=1}^{i=15} r_i \exp [-k (t_i + t_c)]$$

$$= (0.2) (3.53 \times 10^3) (5 \times 10^6) (0.0667) \sum_{t_i=1}^{t_i=15} \exp [-0.2 (t_i + t_c)]$$

$$= 23.54 \times 10^7 \sum_{t_i=1}^{t_i=15} \exp [-0.2 (t_i + t_c)] \text{ in } ft^3 \frac{CH_4}{yr}$$

5. The methane gas generation rate before closure can be calculated by:

$$\frac{dG}{dt} \text{ (before closure)} = (k L_o M_n) \sum_{t_i=1}^{t_i=n} \frac{\exp (-k t_i)}{(n)}$$

where, M_n = amount of refuse accumulated over n years.

n = number of years since the initial placement of refuse but before closure

$$\frac{dG}{dt} \text{ (before closure)} = \frac{(0.2)(3.53 \times 10^3)}{n} M_n \sum_{t_i = 1}^{t_i = n} \exp(-0.2t_i)$$

Figure D-5 shows the methane generation rate as a function of time.

D.2 Alternative Methods

The emission factor method, the SCAQMD method, and the Municipal Waste Generation method are examples of alternative techniques for estimating landfill air emissions. A comparison of these methods to the Scholl Canyon method is presented in Table D-1. Section D.2.1 describes the emission factor method, while the SCAQMD method and the Municpal Waste Generation method are described in Sections D.2.2 and D.2.3, respectively.

D.2.1 Emission Factor Method.

The emission factor method, like the Scholl Canyon method uses information from the EPA survey of municipal landfills to predict nationwide emission estimates. The design capacity of each eligible landfill is scaled using the appropriate factor, as discussed in Section 3.3.4, and multiplied by an emission factor based on the location of the landfill. The SCAQMD emission factor 13.6 tons NMOC/million tons of refuse-yr and a 2.6 location factor (accounting for gas generation in wet states) can be used. A "wet" state is defined as a state with an annual precipitation of at least 23 inches. Figure D-6 illustrates the calculation scheme.

D.2.2 SCAQMD Method.

An alternate method of estimating the current nationwide landfill air emission rate is to use the SCAQMD 1984 approach which estimated 300 million metric tons of refuse accumulated over 26 years (1957-1983) for 10 million people in the South Coast Air Basin.

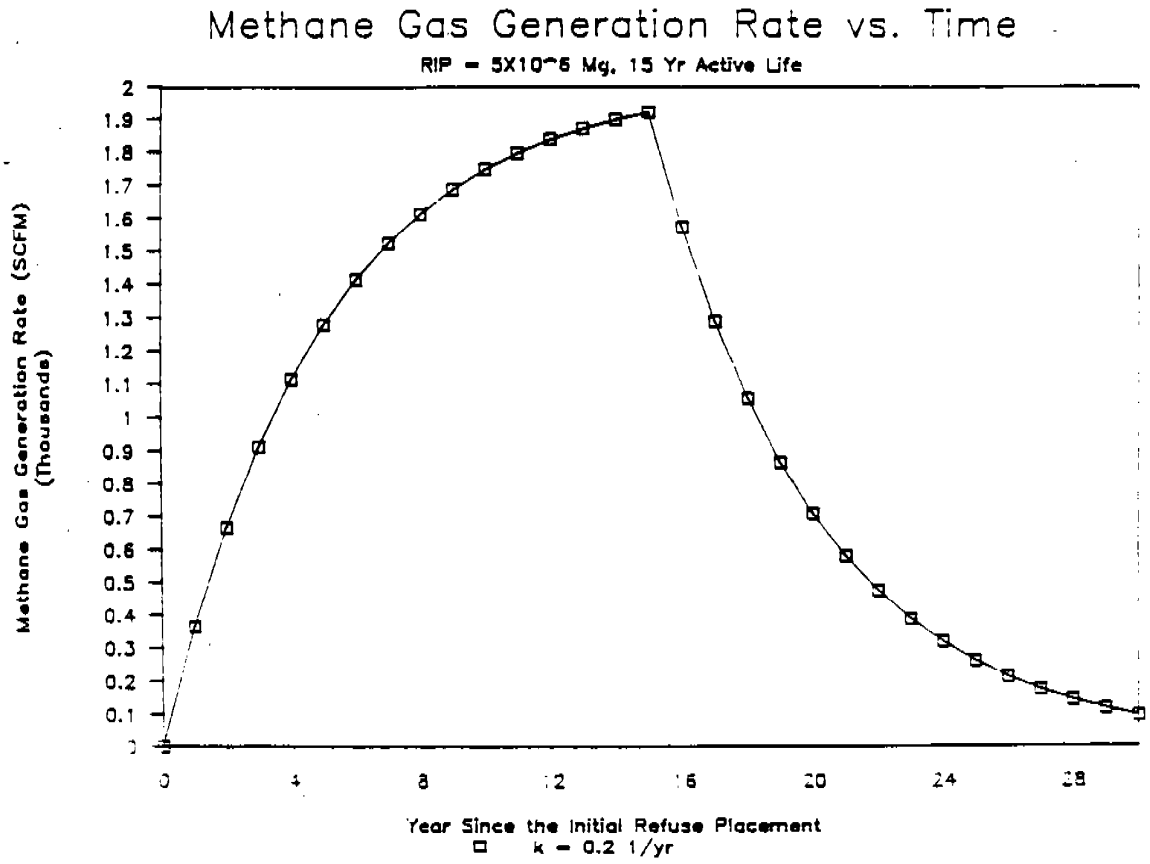


Figure D-5. Methane generation rate as a function of time.

TABLE D-1. NATIONWIDE NMOC EMISSION RATE FROM EXISTING LANDFILLS IN 1987.

Source	Landfill air emission estimation method	Thousand Mg NMOC/yr	Comments
EPA LF Survey	Scholl Canyon	200	Potential NMOC emissions from all existing landfills. Reference year 1992.
EPA LF Survey	Emission Factor	335	Potential NMOC emissions from all existing landfills.
SCAQMD 1984	Based on refuse in place in Southern California generated by 10 million people.	243	"Current" NMOC emissions from all existing active and closed landfills.
1986 EPA-sponsored Study	Based on the yearly estimates of municipal generated from 1960 to 2000.	74.8	"Current" NMOC emissions from all existing active and closed landfills.

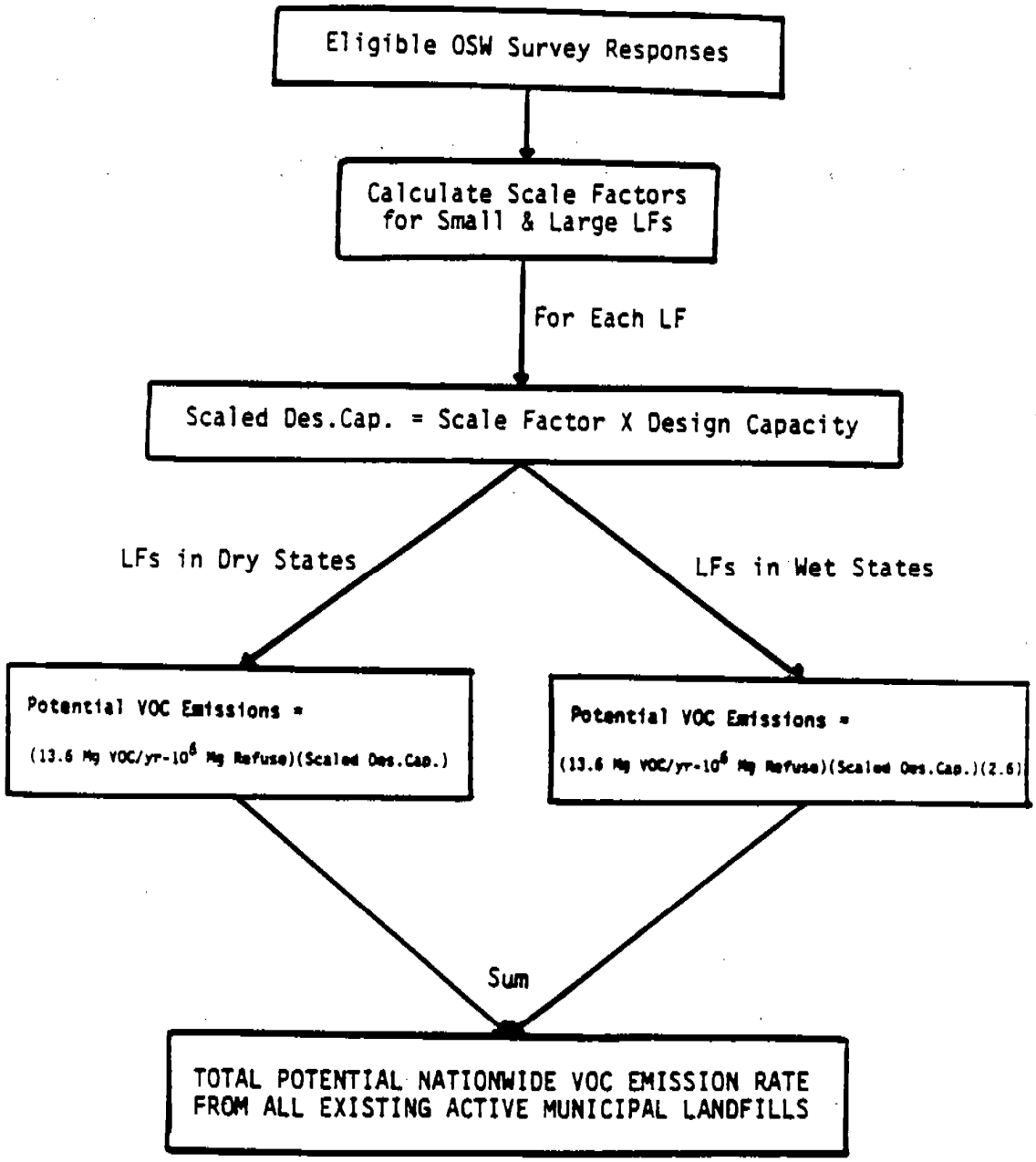


Figure D-6. Calculation schematics for emission factor method.

The in-place refuse for the South Coast in 1983 was estimated using the refuse generation rate per capita and population estimates:

The major assumptions made in the South Coast study were:

- The average refuse generation rate of 7.9 lbs refuse/capita-day was assumed to be constant over the 26 year period.
- Refuse has been accumulated since 1957. (Prior to 1957, most of refuse was incinerated).
- All municipal waste generated is disposed in landfills.

The nationwide landfill air emission rate can be estimated by scaling the SCAQMD refuse in place to the national level. The following additional assumptions were made to scale to the national level:

- 15 percent of the U.S. population lives in "dry" states and 85% lives in "wet" states.
- The U.S. population in 1987 is 277 million.
- The SCAQMD emission factor of 13.6 Mg VOC/million Mg of refuse-yr is used.
- The emission rate from landfills in "wet" states (>21" of annual precipitation) is 2.6 times greater on a per Mg of refuse basis.

Calculation of the Nationwide landfill air emission rate using this approach is shown below:

- Current Nationwide VOC Emission Rate from Wet States,

$$= \frac{300 \times 10^6 \text{ Mg refuse}}{10 \times 10^6 \text{ people}} \times 277 \times 10^6 \text{ people} \times 0.85 \times$$

$$\frac{13.6 \text{ Mg VOC}}{\text{yr} - 10^6 \text{ Mg refuse}} \times 2.6 = 249{,}800 \text{ Mg VOC/yr}$$

- Current Nationwide VOC Emission Rate from Dry States,

$$= \frac{300 \times 10^6 \text{ Mg refuse}}{10 \times 10^6 \text{ people}} \times 277 \times 10^6 \text{ people} \times 0.15 \times$$

$$\frac{13.6 \text{ Mg VOC}}{\text{yr} - 10^6 \text{ Mg refuse}} = 16{,}950 \text{ Mg VOC/yr}$$

- Total Current Nationwide VOC Emission Rate = 267,000 Mg VOC/yr

D.2.3 Municipal Waste Generation Rate Method. The municipal solid waste generation rate from 1960 to 2000 was integrated over the period of 1960 to 1987 (see Figure D-7)[3] to yield the total amount of municipal waste generated over the past 27 years. By assuming that 85 percent of the municipal waste generated is disposed by landfill methods and 85 percent of the U.S.A. population lives in "wet" states, the nationwide landfill air emission rate based on the municipal waste generation rate can be calculated. The assumption that 85 percent of the nationwide municipal waste is based on the estimate provided in an EPA study.[4] The remaining 15 percent is reportedly combusted.

The nationwide landfill air emission rates from new landfills were then calculated using the same calculation scheme shown in Figure D-6. The national potential landfill air emission rate in 1993 and actual landfill air emissionrate expected in 1993 from new landfills are estimated to be 52,000 megagrams/yr and 16,000 megagrams/yr, respectively. The results are also shown in Table D-1.

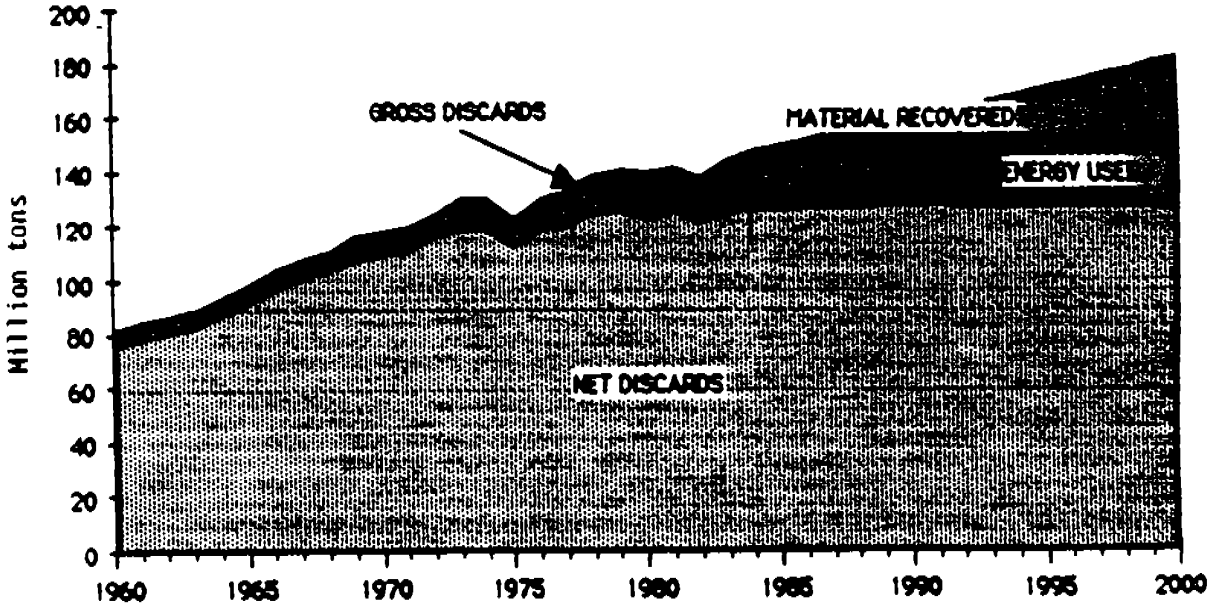


Figure D-7. Gross discards, materials recovery, energy recovery, and discards of municipal solid waste 1960 to 2000.

D.3 REFERENCES

1. Emcon Associates. Methane Generation and Recovery from Landfills. Ann Arbor, Ann Arbor Science. 1982.

2. Reference 1.

3. Franklin Associates, Ltd. Characterization of Municipal Solid Waste in the United States, 1960 to 2000. Final Report. July 11, 1986.

4. The U.S. Environmental Protection Agency. Municpal Waste Combustion Study - Characterization of the Municipal Waste Combustion Industry. EPA/530-SW-87-021h. June 1987.

APPENDIX E

TEST METHODS AND PROCEDURES

APPENDIX E

TEST METHODS AND PROCEDURES

Appendix E contains the three test methods developed by EPA for proposal as part of this rulemaking. These include proposed Method 23 - Determination of Landfill Gas Production Flow Rate, which begins on the following page, proposed Method 3C - Determination of Carbon Dioxide, Methane, Nitrogen, and Oxygen from Stationary Sources, which begins on page E-21, and proposed Method 25C - Determination of Nonmethane Organic Compounds (NMOC) in Landfill Gas, which begins on page E-27.

APPENDIX E - REFERENCE METHODS

METHOD 2E - DETERMINATION OF LANDFILL GAS GAS PRODUCTION FLOW RATE

1. Applicability and Principle

1.1 Applicability. This method applies to the measurement of landfill gas (LFG) production flow rate from municipal solid waste landfills and is used to calculate the flow rate of nonmethane organic compounds (NMOC) from landfills.

1.2 Principle. Extraction wells are installed either in a cluster of three or at five dispersed locations in the landfill. A blower is used to extract LFG from the landfill. LFG composition, landfill pressures, and orifice pressure differentials from the wells are measured and the landfill gas production flow rate is calculated.

1.3 Safety. Since this method is complex, experienced personnel only should perform the test. Explosion-proof equipment shall be used for testing because of the potential explosion hazard of the landfill gas. No smoking shall be allowed on the landfill site during testing. Breathing protection is recommended.

2. Apparatus

2.1 Well Drilling Rig. Capable of boring a 24-in. diameter hole into the landfill to a minimum of 75 percent of the landfill depth. The depth of the well shall not exceed the bottom of the landfill or the liquid level.

2.2 Gravel. No fines, 1 to 3 in. in diameter.

2.3 Bentonite.

2.4 Backfill Material. Clay, soil, and sandy loam have been found to be acceptable.

2.5 Extraction Well Pipe. Polyvinyl chloride (PVC), high density polyethylene (HDPE), fiberglass, or stainless steel, with a minimum diameter of 4 in.

2.6 Well Assembly. PVC ball or butterfly valve, sampling ports at the well head and outlet, and an in-line orifice meter. A schematic of the well assembly is shown in Figure 1.

2.7 Cap. PVC or HDPE.

2.8 Header Piping. PVC or HDPE.

2.9 Auger. Capable of boring a 6- to 9-in. diameter hole to a depth equal to the top of the perforated section of the extraction well, for pressure probe installation.

2.10 Pressure Probe. PVC or stainless steel (316), 1-in. Schedule 40 pipe. Perforate the bottom two thirds. A minimum requirement for perforations is with four 1/4-in. diameter holes spaced 90^{o} apart every 6 in.

2.11 Blower and Flare Assembly. Explosion-proof blower, capable of pulling a vacuum of 25 in. H_2O and of extracting LFG at a flow rate of 300 ft^3/min, a water knockout, and flare or incinerator.

2.12 Standard Pitot Tube and Differential Pressure Gauge for Flow Rate Calibration with Standard Pitot. Same as Method 2, Sections 2.7 and 2.8.

2.13 Orifice Meter. Orifice plate, pressure tabs, and pressure measuring device to measure the LFG flow rate.

2.14 Barometer. Same as Method 4, Section 2.1.5.

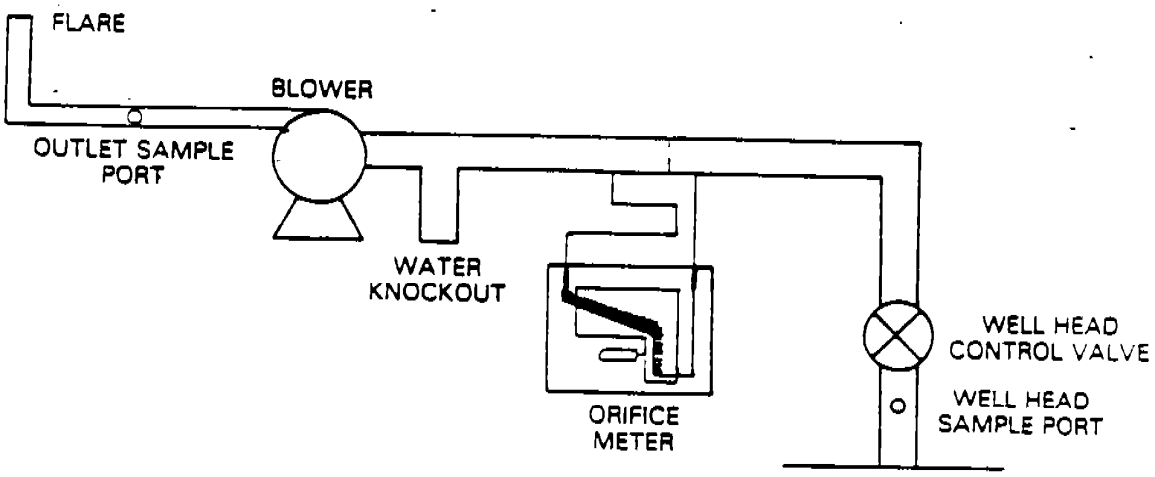


Figure 1. Schematic of above ground assembly.

2.15 Differential Pressure Gauge. Water-filled U-tube manometer or equivalent, capable of measuring within 0.01 in. H_2O, for measuring the pressure of the pressure probes.

3. Procedure

3.1 Placement of Extraction Wells. The landfill owner or operator may install a single cluster of three extraction wells in a test area or space five wells over the landfill. The cluster wells are recommended but may be used only if the composition, age of the refuse, and the landfill depth of the test area can be determined.

3.1.1 Cluster Wells. Consult landfill site records for the age of the refuse, depth, and composition of various sections of the landfill. Select an area near the perimeter of the landfill with a depth equal to or greater than the average depth of the landfill and with the average age of the refuse between 2 and 10 years old. Avoid areas known to contain nondecomposable materials, such as concrete and asbestos. Locate wells as shown in Figure 2.

3.1.1.1 The age of the refuse in a test area will not be uniform, so calculate a weighted average to determine the average age of the refuse as follows.

$$A_{avg} = \sum_{i=1}^{n} f_i \, A_i$$

where,

A_{avg} = Average age of the refuse tested, yr.

f_i = Fraction of the refuse in the i^{th} section.

A_i = Age of the i^{th} fraction, yr.

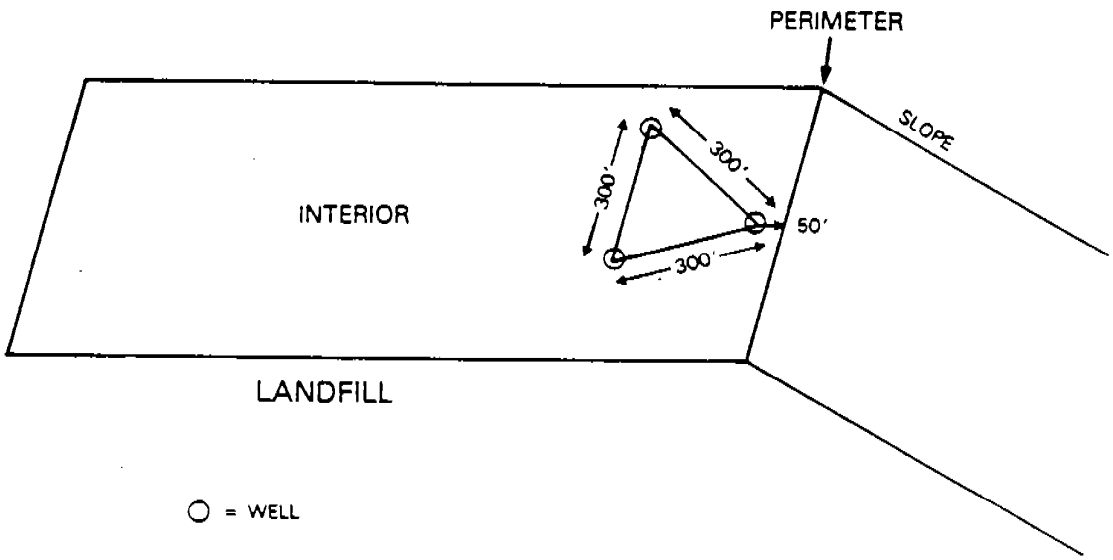


Figure 2. Cluster well placement.

3.1.2 Equal Volume Wells. Divide the sections of the landfill that are at least 2 years old into five areas representing equal volumes. Locate an extraction well near the center of each area.

3.2 Installation of Extraction Wells. Use a well drilling rig to dig a 24-in. diameter hole in the landfill to a minimum of 75 percent of the landfill depth, not to exceed the bottom of the landfill or the liquid level. Perforate the bottom two thirds of the extraction well pipe. A minimum requirement for perforations is with four 1/2-in. diameter holes spaced 90^{0} apart every 4 to 8 in. Place the extraction well in the center of the hole and backfill with gravel to a level 1 ft above the perforated section. Add a layer of backfill material 4 ft thick. Add a layer of bentonite 3 ft thick, and backfill the remainder of the hole with cover material or material equal in permeability to the existing cover material. The specifications for extraction well installation are shown in Figure 3.

3.3 Pressure Probes. Locate pressure probes along three radial arms approximately 120^{0} apart at distances of 10, 50, 100, and 150 ft from the extraction well. The tester has the option of locating additional pressure probes at distances every 50 feet beyond 150 ft. Example placements of probes are shown in Figure 4. The probes 50, 100, and 150 ft (and any additional probes located along the three radial arms) from each well (deep probes) shall extend to a depth equal to the top of the perforated section of the extraction wells. All other probes (shallow probes) shall extend to a depth equal to half the depth of the deep probes.

3.3.1 Use an auger to dig a hole, 6- to 9-in. in diameter, for each pressure probe. Perforate the bottom two thirds of the pressure probe. A minimum requirement for perforations is four 1/4-in. diameter

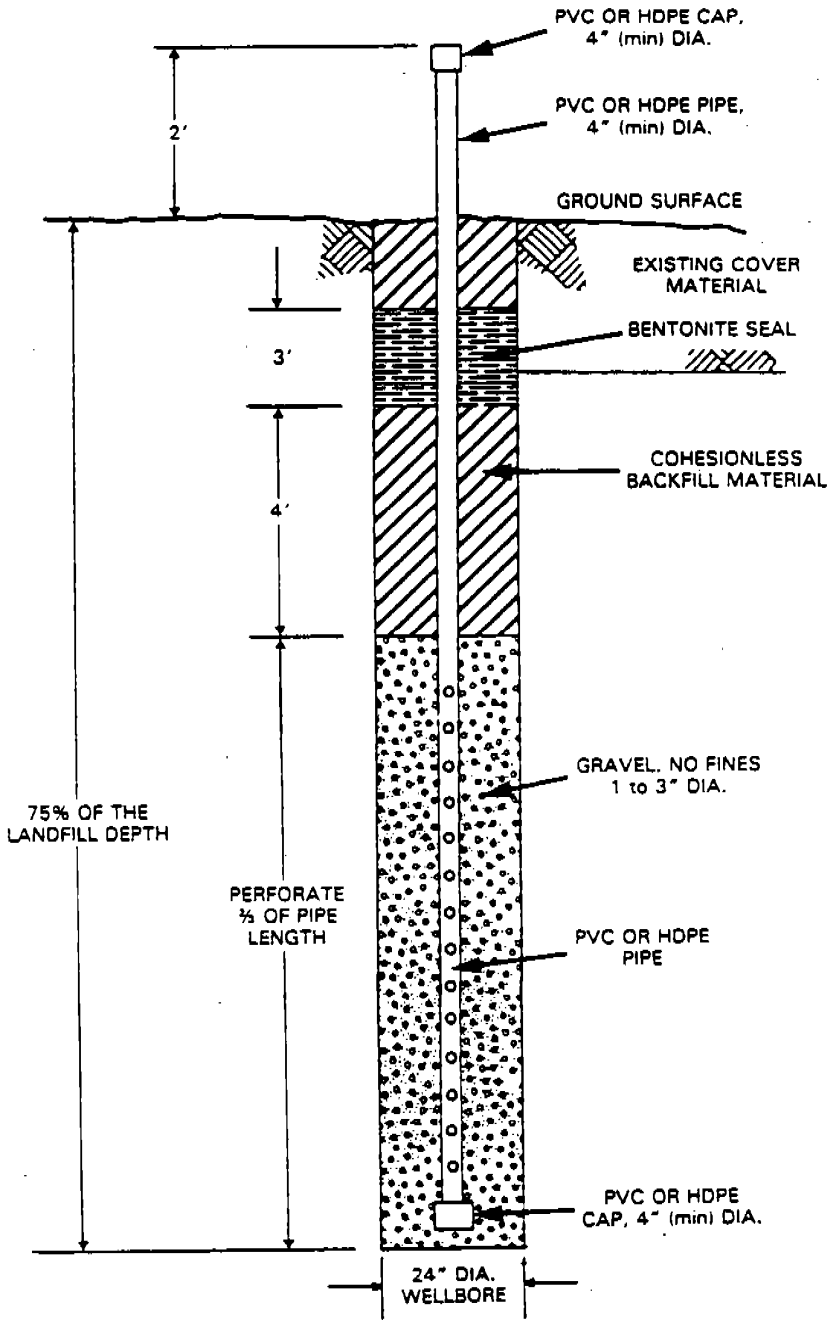


Figure 3. Gas extraction well.

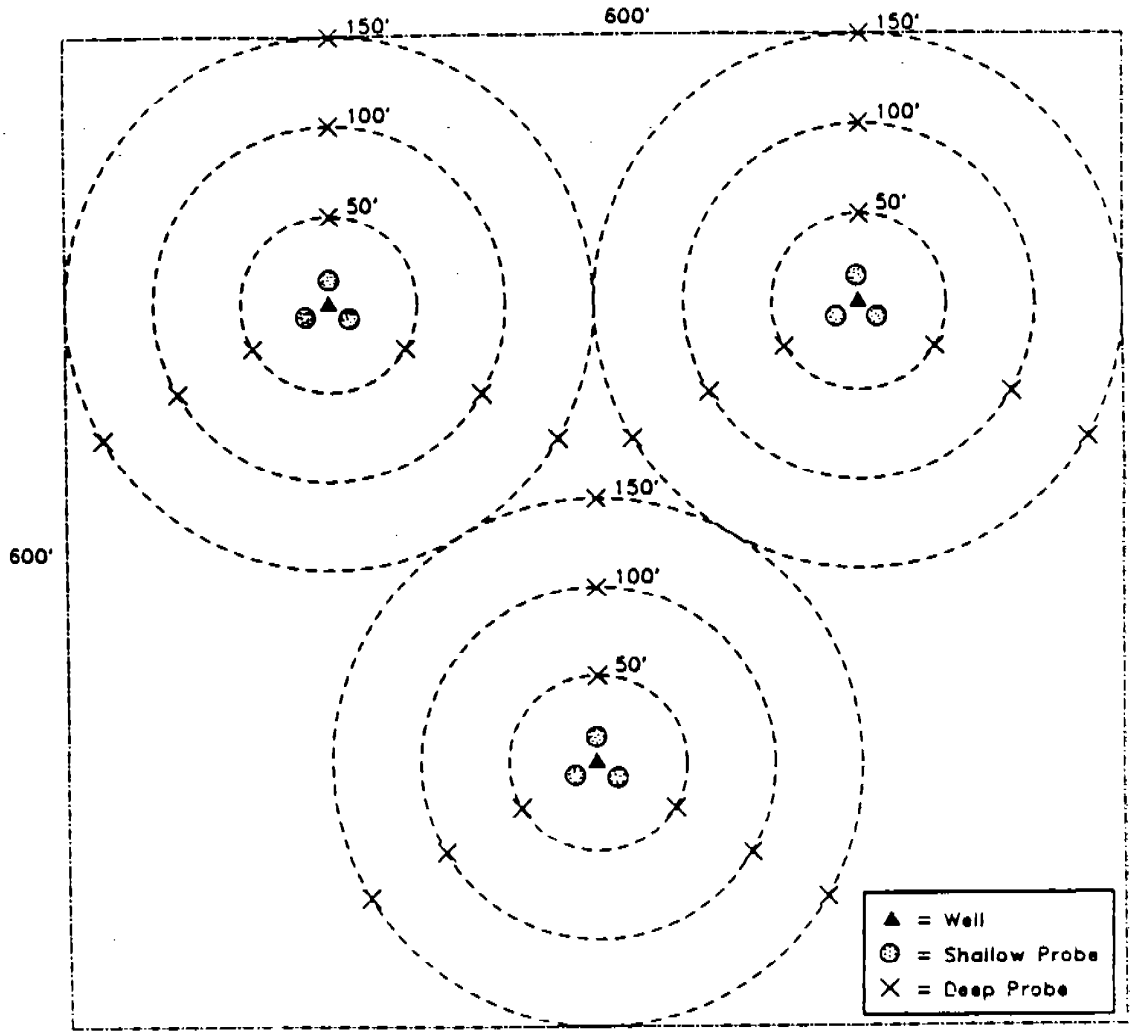


Figure 4. Cluster well configuration.

holes spaced 90^0 apart every 6 in. Place the pressure probe in the center of the hole and backfill with gravel to a level 1 ft above the perforated section. Add a layer of backfill material at least 4 ft thick. Add a layer of bentonite at least 1 ft thick, and backfill the remainder of the hole with cover material or material equal in permeability to the existing cover material. The specifications for pressure probe installation are shown in Figure 5.

3.4 LFG Flow Rate Measurement. Locate an orifice meter as shown in Figure 1. Attach the wells to the blower and flare assembly. The individual wells may be ducted to a common header so that a single blower and flare assembly and orifice meter may be used. Use the procedures in Section 4.1 to calibrate the orifice meter.

3.5 Leak Check. A leak check of the above ground system is required for accurate flow rate measurements and for safety. Sample LFG at the well head sample port and at the outlet sample port. Use Method 3C to determine nitrogen (N_2) concentrations. Determine the difference by using the formula below.

$$\text{Difference} = C_o - C_w$$

where,

C_w = Concentration of N_2 at the wellhead, ppm.

C_o = Concentration of N_2 at the outlet, ppm.

The system passes the leak check if the difference is less than 10,000.

3.6 Static Testing. Close the control valves on the wells during static testing. Measure the gauge pressure (P_g) at each deep pressure probe and the barometric pressure (P_{bar}) every 8 hr for 3 days.

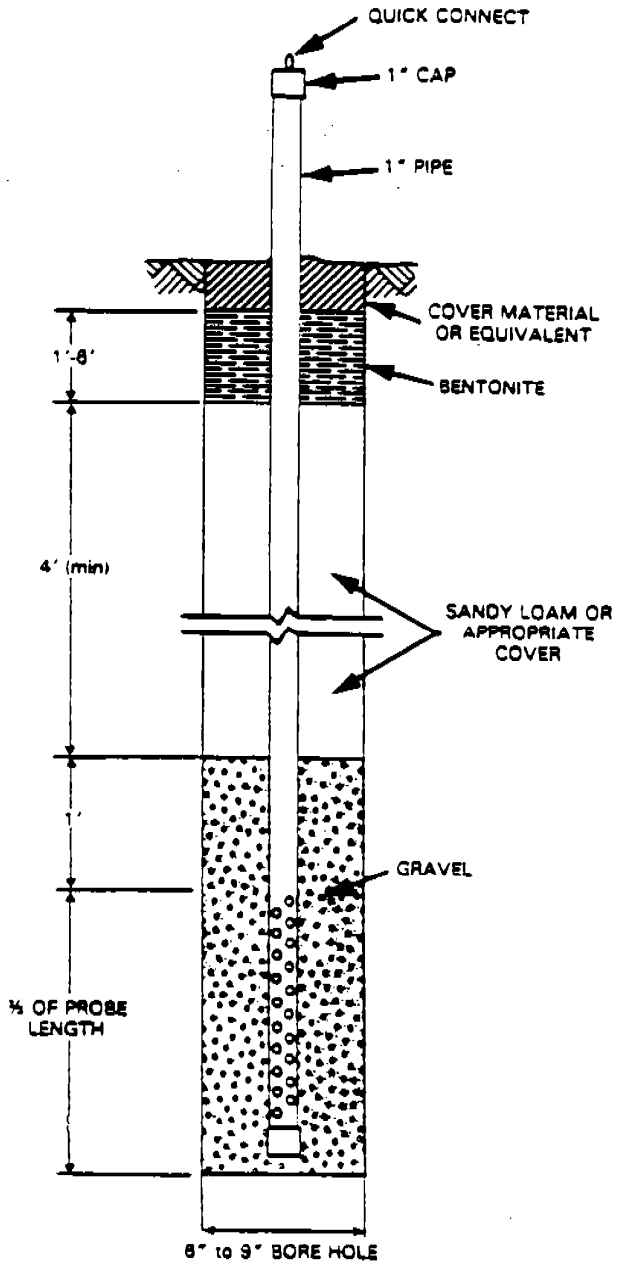


Figure 5. Pressure probe.

Convert the gauge pressure (in. H_2O) of each deep pressure probe to absolute pressure (in. H_2O) by using the following equation. Record as P_i.

$$P_i \text{ (in. } H_2O) = (0.5353)\ P_{bar} \text{ (mm Hg)} + P_g \text{ (in. } H_2O)$$

3.6.1 For each probe, average all of the 8-hr deep pressure probe readings and record as P_{ia}. P_{ia} is used in Section 3.7.6 to determine the maximum radius of influence.

3.6.2 Measure the static flow rate of each well once during static testing.

3.7 Short Term Testing. The purpose of short term testing is to determine the maximum vacuum that can be applied to the wells without infiltration of air into the landfill. The short term testing is done on one well at a time. Burn all LFG with a flare or incinerator.

3.7.1 Use the blower to extract LFG from a single well at twice the static flow rate of the respective well measured in Section 3.6.2. If using a single blower and flare assembly and a common header system, close the control valve on the wells not being measured. Allow 24 hr for the system to stabilize at this flow rate.

3.7.2 Test for infiltration of air into the landfill by measuring the gauge pressures of the shallow pressure probes and using Method 3C to determine the LFG N_2 concentration. If the LFG N_2 concentration is less than 1 percent and all of the shallow probes have a positive gauge pressure, increase the blower vacuum by 2 in. H_2O, wait 24 hr, and repeat the tests for infiltration. Continue the above steps of increasing blower vacuum by 2 in. H_2O, waiting 24 hr, and testing for infiltration until the concentration of N_2 exceeds 1 percent or any of

the shallow probes have a negative gauge pressure, at which time reduce the blower vacuum so that the N_2 concentration is less than 1 percent and the gauge pressures of the shallow probes are positive.

3.7.3 At this blower vacuum, measure P_{bar} every 8 hr for 24 hr and record the LFG flow rate as Q_s and the probe gauge pressures for all of the probes as P_f. Convert the gauge pressures of the deep probes to absolute pressures for each 8 hr reading at Q_s as follows.

$$P_f \text{ (in. } H_2O) = (0.5353)\ P_{bar} \text{ (mm Hg)} + P_f \text{ (in. } H_2O)$$

3.7.4 For each probe, average the 8-hr deep pressure probe readings and record as P_{fa}.

3.7.5 For each probe, compare the initial average pressure (P_{ia}) from Section 3.6.1 to the final average pressure (P_{fa}). Determine the furthermost point from the well head along each radial arm where $P_{fa} \leq P_{ia}$. This distance is the maximum radius of influence, which is the distance from the well affected by the vacuum. Average these values to determine the average maximum radius of influence (R_{ma}).

3.7.7 Calculate the depth (D) affected by the extraction well as follows.

$$D_{st} = WD + R_{ma}$$

where,

WD = Well depth, ft.

3.7.8 Calculate the void volume for the extraction well (V) as follows.

$$V = 0.40 \quad R_{ma}^{2} \, D_{st}$$

3.7.9 Repeat the procedures in Section 3.7 for each well.

3.8 Calculate the total void volume of the test wells (V_v) by summing the void volumes (V) of each well.

3.9 Long Term Testing. The purpose of long term testing is to extract two void volumes of LFG from the extraction wells. Use the blower to extract LFG from the wells. If a single blower and flare assembly and common header system are used, open all control valves and set the blower vacuum equal to the highest stabilized blower vacuum demonstrated by any individual well in Section 3.7. Every 8 hr, sample the LFG from the well head sample port, measure the gauge pressures of the shallow pressure probes, the blower vacuum, the LFG flow rate, and use the criteria for infiltration in Section 3.7.2 and Method 3C to test for infiltration. If Infiltration is detected, do not reduce the blower vacuum, but reduce the LFG flow rate from the well by adjusting the control valve on the well head. Continue until the equivalent of two total void volumes (V_v) have been extracted, or until $V_t = 2 \, V_v$.

3.9.1 Calculate V_t, the total volume of LFG extracted from the wells, as follows.

$$V_t = \sum_{i=1}^{n} 60 \, Q_i \, t_{vi}$$

where,

V_t = Total volume of LFG extracted from wells, ft^3.

Q_i = LFG flow rate measured at orifice meter at the ith interval, ft^3/min.

t_{vi} = Time of the ith interval (usually 8), hr.

3.9.2 Record the final stabilized flow rate as Q_f. If, during the long term testing, the flow rate does not stabilize, calculate Q_f by averaging the last 10 recorded flow rates.

3.9.3 For each deep probe, convert each gauge pressure to absolute pressure as in Section 3.7.4. Average these values and record as P_{sa}. For each probe, compare P_{ia} to P_{sa}. Determine the furthermost point from the well head along each radial arm where $P_{sa} \leq P_{ia}$. This distance is the stabilized radius of influence. Average these values to determine the average stabilized radius of influence (R_{sa}).

3.10 Determine the NMOC mass emission rate using the procedures in Section 5.

4. Calibrations

4.1 Orifice Calibration Procedure. Locate a standard pitot tube in line with an orifice meter. Use the procedures in Section 3 of Method 2 to determine the average dry gas volumetric flow rate for at least five flow rates that bracket the expected LFG flow rates, except in Section 3.1, use a standard pitot tube rather than a Type S pitot tube. Method 3C may be used to determine the dry molecular weight. It may be necessary to calibrate more than one orifice meter in order to bracket the LFG flow rates. Construct a calibration curve by plotting the pressure drops across the orifice meter for each flow rate versus the average dry gas volumetric flow rate in ft^3/min of the gas.

5. Calculations

5.1 Nomenclature.

A_{avg} = Average age of the refuse tested, yr.

A_i = Age of refuse in the i^{th} fraction, yr.

A = Age of landfill, yr.

A_r = Acceptance rate, Mg/yr.

C = NMOC concentration, ppm.

D = Depth affected by the test wells, ft.

D_{st} = Depth affected by the test wells in the short term test, ft.

f = Fraction of decomposable refuse in the landfill.

f_i = Fraction of the refuse in the i^{th} section.

k = Landfill gas generation constant, yr^{-1}.

L_o = Methane generation potential, ft^3/Mg.

L_o' = Revised methane generation potential to account for the amount of nondecomposable material in the landfill, ft^3/Mg.

M_i = Mass of refuse of the i^{th} section, Mg.

M_r = Mass of decomposable refuse affected by the test well, Mg.

P_{bar} = Atmospheric pressure, mm Hg.

P_g = Gauge pressure of the deep pressure probes, in. H_2O.

P_i = Initial absolute pressure of the deep pressure probes during static testing, in. H_2O.

P_{ia} = Average initial absolute pressure of the deep pressure probes during static testing, in. H_2O.

P_f = Final absolute pressure of the deep pressure probes during short term testing, in. H_2O.

P_{fa} = Average final absolute pressure of the deep pressure probes during short term testing, in. H_2O.

P_s = Final absolute pressure of the deep pressure probes during long term testing, in. H_2O.

P_{sa} = Average final absolute pressure of the deep pressure probes during long term testing, in. H_2O.

Q_f = Final stabilized flow rate, ft^3/min.

Q_i = LFG flow rate measured at orifice meter during the i^{th} interval, ft^3/min.

Q_s = Maximum LFG flow rate at each well determined by short term test, ft^3/min.

Q_t = NMOC mass emission rate, ft^3/min.

R_m = Maximum radius of influence, ft.

R_{ma} = Average maximum radius of influence, ft.

R_s = Stabilized radius of influence for an individual well, ft.

R_{sa} = Average stabilized radius of influence, ft.

t_i = Age of section i, yr.

t_t = Total time of long term testing, yr.

V = Void volume of test well, ft^3.

V_r = Volume of refuse affected by the test well, ft^3.

V_t = Total volume of refuse affected by the long term testing, ft^3.

V_v = Total void volume affected by test wells, ft^3.

WD = Well depth, ft.

ρ = refuse density, Mg/ft^3 (Assume 0.018 Mg/ft^3 if data are unavailable).

5.2 Use the following equation to calculate the depth affected by the test well. If using cluster wells, use the average depth of the wells for WD.

$$D = WD + R_{sa}$$

5.3 Use the following equation to calculate the volume of refuse affected by the test well.

$$V_r = R_{sa} \pi D$$

5.4 Use the following equation to calculate the mass affected by the test well.

$$M_r = V_r \rho$$

5.5 Modify L_o to account for the nondecomposable refuse in the landfill.

$$L_o' = f L_o$$

5.6 In the following equation, solve for k by iteration. A suggested procedure is to select a value for k, calculate the left side

of the equation, and if not equal to zero, select another value for k. Continue this process until the left hand side of the equation equals zero, ±0.001.

$$k\, e^{-k A_{avg}} - \left[\frac{Q_f}{2\, L_o'\, M_r} \right] = 0$$

5.7 Use the following equation to determine landfill NMOC mass emission rate if the yearly acceptance rate of refuse has been consistent (±10 percent) over the life of the landfill.

$$Q_t = 2\, L_o'\, A_r\, (1 - e^{-k A})\, C\, (1.018 \times 10^{-10})$$

5.8 Use the following equation to determine landfill NMOC mass emission rate if the acceptance rate has not been consistent over the life of the landfill.

$$Q_t = 2\, k\, L_o'\, C\, (1.018 \times 10^{-10}) \sum_{i=1}^{n} M_i\, e^{-kt_i}$$

6. Bibliography

1. Same as Method 2, Appendix A, 40 CFR Part 60.

2. Emcon Associates, Methane Generation and Recovery from Landfills. Ann Arbor Science, 1982.

3. The Johns Hopkins University, Brown Station Road Landfill Gas Resource Assessment, Volume 1: Field Testing and Gas Recovery Projections. Laurel, Maryland: October 1982.

4. Mandeville and Associates, Procedure Manual for Landfill Gases Emission Testing.

5. Letter and attachments from Briggum, S., Waste Management of North America, to Thorneloe, S., EPA. Response to July 28, 1988 request for additional information. August 18,1988.

6. Letter and attachments from Briggum, S., Waste Management of North America, to Wyatt, S., EPA. Response to December 7, 1988 request for additional information. January 16, 1989.

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METHOD 3C - DETERMINATION OF CARBON DIOXIDE, METHANE, NITROGEN, AND OXYGEN FROM STATIONARY SOURCES

1. Applicability and Principle

1.1 Applicability. This method applies to the analysis of carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2), and oxygen (O_2) in samples from municipal landfills and other sources when specified in an applicable subpart of the regulations.

1.2 Principle. A portion of the sample is injected into a gas chromatograph (GC) and the CO_2, CH_4, N_2, and O_2 concentrations are determined by using a thermal conductivity detector (TCD) and integrator.

2. Range and Sensitivity

2.1 Range. The range of this method depends upon the concentration of samples. The analytical range of TCD's is generally between approximately 10 ppm and the upper percent range.

2.2 Sensitivity. The sensitivity limit for a compound is defined as the minimum detectable concentration of that compound, or the concentration that produces a signal-to-noise ratio of three to one. For CO_2, CH_4, N_2, and O_2, the sensitivity limit is in the low ppm range.

3. Interferences

Since the TCD exhibits universal response and detects all gas components except the carrier, interferences may occur. Choosing the appropriate GC or shifting the retention times by changing the column flow rate may help to eliminate resolution interferences.

To assure consistent detector response, helium is used to prepare calibration gases. Frequent exposure to samples or carrier gas containing oxygen may gradually destroy filaments.

4. Apparatus

4.1 Gas Chromatograph. GC having at least the following components:

4.1.1 Separation Column. Appropriate column(s) to resolve CO_2, CH_4, N_2, O_2, and other gas components that may be present in the sample. One column that has been advertised to work in this case is column CTR I available from Alltech Associates Inc., 2051 Waukegan Road, Deerfield, Illinois 60015. NOTE: Mention of trade names or specific products does not constitute endorsement or recommendation by the U. S. Environmental Protection Agency.

4.1.2 Sample Loop. Teflon or stainless steel tubing of the appropriate diameter. NOTE: Mention of trade names or specific products does not constitute endorsement or recommendation by the U. S. Environmental Protection Agency.

4.1.3 Conditioning System. To maintain the column and sample loop at constant temperature.

4.1.4 Thermal Conductivity Detector.

4.2 Recorder. Recorder with linear strip chart. Electronic integrator (optional) is recommended.

4.3 Teflon Tubing. Diameter and length determined by connection requirements of cylinder regulators and the GC.

4.4 Regulators. To control gas cylinder pressures and flow rates.

4.5 Adsorption Tubes. Applicable traps to remove any O_2 from the carrier gas.

5. Reagents

5.1 Calibration and Linearity Gases. Standard cylinder gas mixtures for each compound of interest with at least three concentration levels spanning the range of suspected sample concentrations. The calibration gases shall be prepared in helium.

5.2 Carrier Gas. Helium, high-purity.

6. Analysis

6.1 Sample Collection. Use the sample collection procedures described in Methods 3 or 25C to collect a sample of landfill gas (LFG).

6.2 Preparation of GC. Before putting the GC analyzer into routine operation, optimize the operational conditions according to the manufacturer's specifications to provide good resolution and minimum analysis time. Establish the appropriate carrier gas flow and set the detector sample and reference cell flow rates at exactly the same levels. Adjust the column and detector temperatures to the recommended levels. Allow sufficient time for temperature stabilization. This may typically require 1 hour for each change in temperature.

6.3 Analyzer Linearity Check and Calibration. Perform this test before sample analysis. Using the gas mixtures in Section 5.1, verify the detector linearity over the range of suspected sample concentrations with at least three points per compound of interest. This initial check may also serve as the initial instrument calibration. All subsequent calibrations may be performed using a single-point standard gas provided the calibration point is within 20 percent of the sample component concentration. For each instrument calibration, record the carrier and detector flow rates, detector filament and block temperatures, attenuation factor, injection time,

chart speed, sample loop volume, and component concentrations. Plot a linear regression of the standard concentrations versus area values to obtain the response factor of each compound. Alternatively, response factors of uncorrected component concentrations (wet basis) may be generated using instrumental integration. NOTE: Peak height may be used instead of peak area throughout this method.

6.4 Sample Analysis. Purge the sample loop with sample, and allow to come to atmospheric pressure before-each injection. Analyze each sample in duplicate, and calculate the average sample area (A). The results are acceptable when the peak areas for two consecutive injections agree within five percent of their average. If they do not agree, run additional samples until consistent area data are obtained. Determine the tank sample concentrations according to Section 7.2.

7. Calculations

Carry out calculations retaining at least one extra decimal figure beyond that of the acquired data. Round off results only after the final calculation.

7.1 Nomenclature.

A = Average sample area.

B_w = Moisture content in the sample, fraction.

C = Component concentration in the sample, dry basis, ppm.

C_t = Calculated NMOC concentration, ppm C equivalent.

C_{tm} = Measured NMOC concentration, ppm C equivalent.

P_{bar} = Barometric pressure, mm Hg.

P_{ti} = Gas sample tank pressure after evacuation, mm Hg absolute.

P_t = Gas sample tank pressure after sampling, but before pressurizing, mm Hg absolute.

P_{tf} = Final gas sample tank pressure after pressurizing, mm Hg absolute.

P_w = Vapor pressure of H_2O (from Table 3C-1), mm Hg.

T_{ti} = Sample tank temperature before sampling, ^oK.

T_t = Sample tank temperature at completion of sampling, ^oK.

T_{tf} = Sample tank temperature after pressurizing, ^oK.

r = Total number of analyzer injections of sample tank during analysis (where j = injection number, 1...r).

R = Mean calibration response factor for specific sample component, area/ppm.

7.2 Concentration of Sample Components. Calculate C for each compound using Equations 3C-1 and 3C-2. Use the temperature and barometric pressure at the sampling site to calculate B_w. If the sample was diluted with helium using the procedures in Method 25C, use Equation 3C-3 to calculate the concentration.

$$B_w = \frac{P_w}{P_{bar}} \qquad \text{3C-1}$$

$$C = \frac{A}{R(1-B_w)} \qquad \text{3C-2}$$

$$C = \left[\frac{\frac{P_{tf}}{T_{tf}}}{\frac{P_t}{T_t} - \frac{P_{ti}}{T_{ti}}}\right] \frac{A}{R(1-B_w)} \qquad \text{3C-3}$$

8. Bibliography

1. McNair, H.M., and E.J. Bonnelli. Basic Gas Chromatography. Consolidated Printers, Berkeley, CA. 1969.

TABLE 3C-1. MOISTURE CORRECTION

Temperature, °C	Vapor pressure of H_2O, mm Hg	Temperature, °C	Vapor pressure of H_2O, mm Hg
4	6.1	18	15.5
6	7.0	20	17.5
8	8.0	22	19.8
10	9.2	24	22.4
12	10.5	26	25.2
14	12.0	28	28.3
16	13.6	30	31.8

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METHOD 25C- DETERMINATION OF NONMETHANE ORGANIC COMPOUNDS (NMOC) IN LANDFILL GASES

1. Applicability and Principle

1.1 Applicability. This method is applicable to the sampling and measurement of nonmethane organic compounds (NMOC) as carbon in landfill gases.

1.2 Principle. A sample probe that has been perforated at one end is driven or augered to a depth of 3 feet (ft) below the bottom of the landfill cover. A sample of the landfill gas is extracted with an evacuated cylinder. The NMOC content of the gas is determined by injecting a portion of the gas into a gas chromatographic column to separate the NMOC from carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4); the NMOC are oxidized to CO_2, reduced to CH_4, and measured by a flame ionization detector (FID). In this manner, the variable response of the FID associated with different types of organics is eliminated.

2. Apparatus

2.1 Sample Probe. Stainless steel, with the bottom third perforated. The sample probe shall be capped at the bottom and shall have a threaded cap with a sampling attachment at the top. The sample probe shall be long enough to go through and extend no less than 3 ft below the landfill cover. If the sample probe is to be driven into the landfill, the bottom cap should be designed to facilitate driving the probe into the landfill.

2.2 Sampling Train.

2.2.1 Rotameter with Flow Control Valve. Capable of measuring a sample flow rate of 100 $\pm$ 10 ml/min. The control valve shall be made of stainless steel.

2.2.2 Sampling Valve. Stainless steel.

2.2.3 Pressure Gauge. U-tube mercury manometer, or equivalent, capable of measuring pressure to within 1 mm Hg in the range of 0 to 1,100 mm Hg.

2.2.4 Sample Tank. Stainless steel or aluminum cylinder, with a minimum volume of 4 liters and equipped with a stainless steel sample tank valve.

2.3 Vacuum Pump. Capable of evacuating to an absolute pressure of 10 mm Hg.

2.4 Purging Pump. Portable, explosion proof, and suitable for sampling NMOC.

2.5 Pilot Probe Procedure. The following are needed only if the tester chooses to use the procedure described in Section 4.2.1.

2.5.1 Pilot Probe. Tubing of sufficient strength to withstand being driven into the landfill by a post driver and an outside diameter of at least 0.25 in. smaller than the sample probe. The pilot probe shall be capped on both ends and long enough to go through the landfill cover and extend no less than 3 ft into the landfill.

2.5.2 Post Driver and Compressor. Capable of driving the pilot probe and the sampling probe into the landfill. The Kitty Hawk portable post driver has been found to be acceptable. NOTE: Mention of trade names or specific products does not constitute endorsement by the Environmental Protection Agency.

2.6 Auger Procedure. The following are needed only if the tester chooses to use the procedure described in Section 4.2.2.

2.6.1 Auger. Capable of drilling through the landfill cover and to a depth of no less than 3 ft into the landfill.

2.6.2 Pea Gravel.

2.6.3 Bentonite.

2.7 NMOC Analyzer, Barometer, Thermometer, and Syringes. Same as in Sections 2.3, 2.4.1, 2.4.2, 2.4.4, respectively, of Method 25.

3. Reagents

3.1 NMOC Analysis. Same as in Method 25, Section 3.2.

3.2 Calibration. Same as in Method 25, Section 3.4, except omit Section 3.4.3.

4. Procedure

4.1 Sample Tank Evacuation and Leak Check. Conduct the sample tank evacuation and leak check either in the laboratory or the field. Connect the pressure gauge and sampling valve to the sample tank. Evacuate the sample tank to 10 mm Hg absolute pressure or less. Close the sampling valve, and allow the tank to sit for 60 minutes. The tank is acceptable if no change is noted. Include the results of the leak check in the test report.

4.2 Sample Probe Installation. The tester may use the procedure in Sections 4.2.1 or 4.2.2. CAUTION: LFG contains methane and therefore explosive mixtures may exist on or near the landfill. It is advisable to take appropriate safety precautions when testing landfills, such as refraining from smoking.

4.2.1 Pilot Probe Procedure. Use the post driver to drive the pilot probe at least 3 ft below the landfill cover. Alternative

procedures to drive the probe into the landfill may be used subject to the approval of the Administrator.

4.2.1.1 Remove the pilot probe and drive the sample probe into the hole left by the pilot probe. The sample probe shall extend at least 3 ft below the landfill cover and shall protrude about 1 ft above the landfill cover. Seal around the sampling probe with bentonite and cap the sampling probe with the sampling probe cap.

4.2.2 Auger Procedure. Use an auger to drill a hole through the landfill cover and to at least 3 ft below the landfill cover. Place the sample probe in the hole and backfill with pea gravel to a level 2 ft from the surface. The sample probe shall protrude at least 1 ft above the landfill cover. Seal the remaining area around the probe with bentonite. Allow 24 hr for the landfill gases to equilibrate inside the augered probe before sampling.

4.3 Sample Train Assembly. Just before assembly, measure the tank vacuum using the pressure gauge. Record the vacuum, the ambient temperature, and the barometric pressure at this time. Assemble the sampling probe purging system as shown in Figure 1.

4.4 Sampling Procedure. Open the sampling valve and use the purge pump and the flow control valve to evacuate at least two sample probe volumes from the system at a flow rate of 100 $\pm$ 10 ml/min. Close the sampling valve and replace the purge pump with the sample tank apparatus as shown in Figure 2. Open the sampling valve and the sample tank valves and, using the flow control valve, sample at a flow rate of 100 $\pm$ 10 ml/min until the sample tank gauge pressure is zero. Disconnect the sampling tank apparatus and use the carrier gas bypass valve to pressurize the sample cylinder to approximately 1,060 mm Hg absolute pressure with helium and record the final pressure.

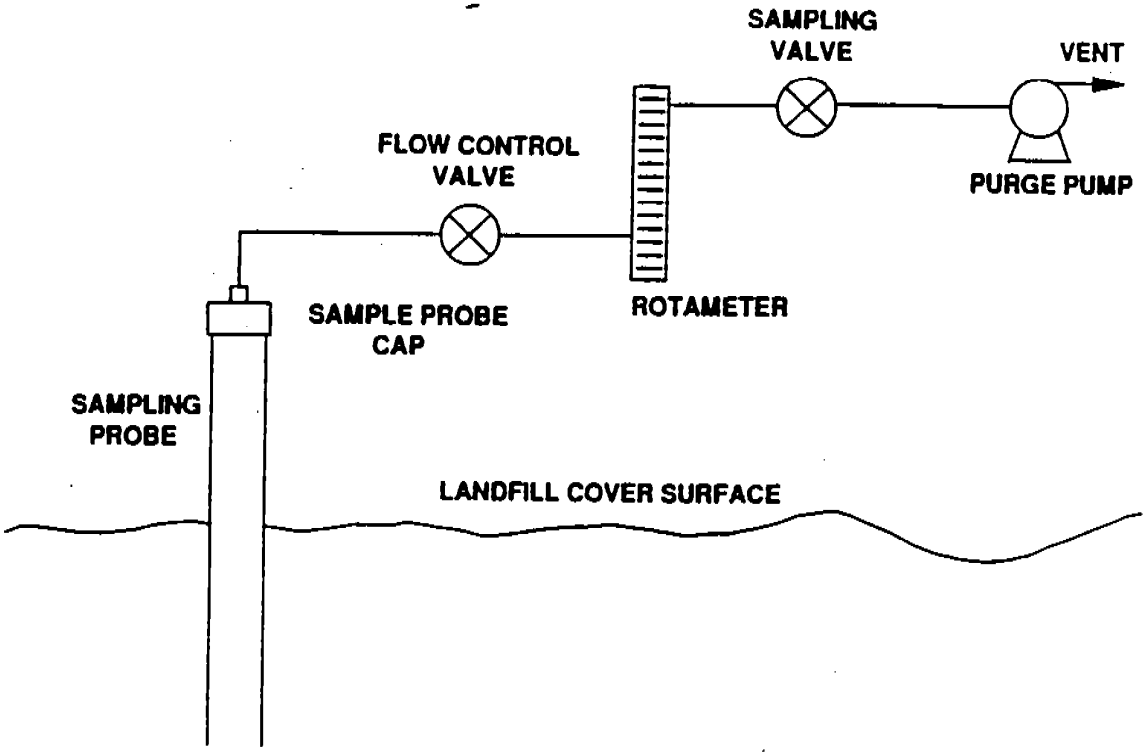


Figure 1. Schematic of sampling probe purging system.

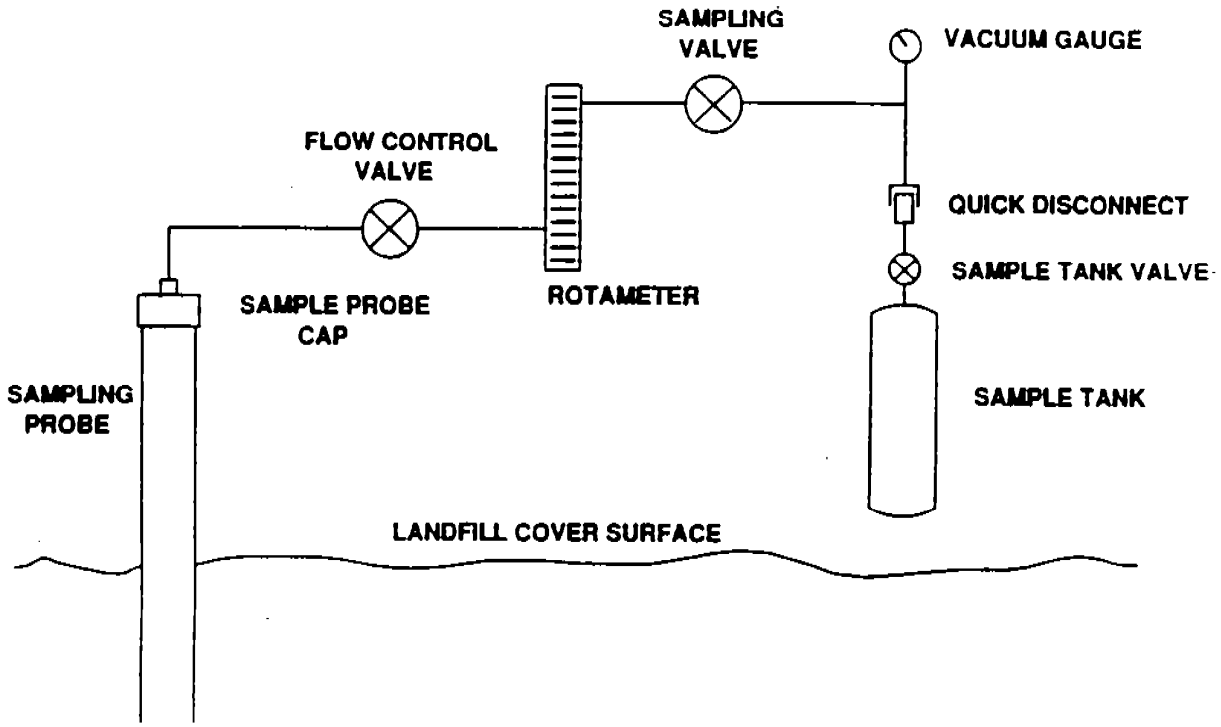


Figure 2. Schematic of sampling train.

Alternatively, the sample tank may be pressurized in the lab. If not analyzing for N_2, the sample cylinder may be pressurized with zero air.

4.4.1 Use Method 3C to determine the percent N_2 in the sample. Presence of N_2 indicates infiltration of ambient air into the gas sample. The landfill sample is acceptable if the concentration of N_2 is less than one percent.

4.5 Analysis. The oxidation, reduction, and measurement of NMOC's is similar to Method 25. Before putting the NMOC analyzer into routine operation, conduct an initial performance test. Start the analyzer, and perform all the necessary functions in order to put the analyzer into proper working order. Conduct the performance test according to the procedures established in Section 5.1. Once the performance test has been successfully completed and the NMOC calibration response factor has been determined, proceed with sample analysis as follows:

4.5.1 Daily Operations and Calibration Checks. Before and immediately after the analysis of each set of samples or on a daily basis (whichever occurs first), conduct a calibration test according to the procedures established in Section 5.2. If the criteria of the daily calibration test cannot be met, repeat the NMOC analyzer performance test (Section 5.1) before proceeding.

4.5.2 Operating Conditions. Same as in Method 25, Section 4.4.2.

4.5.3 Analysis of Sample Tank. Purge the sample loop with sample, and then inject the sample. Under the specified operating conditions, the CO_2 in the sample will elute in approximately 100 seconds. As soon as the detector response returns to baseline following the CO_2 peak, switch the carrier gas flow to backflush, and raise the column oven temperature to 195°C as rapidly as possible. A rate of 30°C/min has

been shown to be adequate. Record the value obtained for any measured NMOC. Return the column oven temperature to 85°C in preparation for the next analysis. Analyze each sample in triplicate, and report the average as C_{tm}.

4.6 Audit Samples. Same as in Method 25, Section 4.5.

5. Calibration and Operational Checks

Maintain a record of performance of each item.

5.1 Initial NMOC Analyzer Performance Test. Same as in Method 25, Section 5.2, except omit the linearity checks for CO_2 standards.

5.2 NMOC Analyzer Daily Calibration.

5.2.1 NMOC Response Factors. Same as in Method 25, Section 5.3.2.

5.3 Sample Tank Volume. The volume of the gas sampling tanks must be determined. Determine the tank volumes by weighing them empty and then filled with deionized water; weigh to the nearest 5 g, and record the results. Alternatively, measure, to the nearest 5 ml, the volume of water used to fill them.

6. Calculations

All equations are written using absolute pressure; absolute pressures are determined by adding the measured barometric pressure to the measured gauge of manometer pressure.

6.1 Nomenclature.

B_w = Moisture content in the sample, fraction.

C_t = Calculated NMOC concentration, ppm C equivalent.

C_{tm} = Measured NMOC concentration, ppm C equivalent.

P_b = Barometric pressure, mm Hg.

P_{ti} = Gas sample tank pressure after evacuation, mm Hg absolute.

P_t = Gas sample tank pressure after sampling, but before pressurizing, mm Hg absolute.

P_{tf} = Final gas sample tank pressure after pressurizing, mm Hg absolute.

P_w = Vapor pressure of H_2O (from Table 1), mm Hg.

T_{ti} = Sample tank temperature before sampling, ^oK.

T_t = Sample tank temperature at completion of sampling, ^oK.

T_{tf} = Sample tank temperature after pressurizing, ^oK.

r = Total number of analyzer injections of sample tank during analysis (where j = injection number, 1...r).

6.2 Water Correction. Use Table 1, the LFG temperature, and barometric pressure at the sampling site to calculate Bw.

$$B_w = \frac{P_w}{P_b}$$

6.3 NMOC Concentration. Use the following equation to calculate the concentration of NMOC for each sample tank.

$$C_t = \left[\frac{\frac{P_{tf}}{T_{tf}}}{\frac{P_t}{T_t} - \frac{P_{ti}}{T_{ti}}}\right]\left[\frac{1}{(1-B_w)\ r}\ \sum_{j=1}^{r} C_{tm}(j)\right]$$

TABLE 25C-1. MOISTURE CORRECTION

Temperature, °C	Vapor pressure of H_2O, mm Hg	Temperature, °C	Vapor pressure of H_2O, mm Hg
4	6.1	18	15.5
6	7.0	20	17.5
8	8.0	22	19.8
10	9.2	24	22.4
12	10.5	26	25.2
14	12.0	28	28.3
16	13.6	30	31.8

7. Bibliography

1. Salo, Albert E., Samuel Witz, and Robert D. MacPhee. Determination of Solvent Vapor Concentrations by Total Combustion Analysis: A Comparison of Infrared with Flame Ionization Detectors. Paper No. 75-33.2. (Presented at the 68th Annual Meeting of the Air Pollution Control Association. Boston, Massachusetts. June 15-20, 1975.) 14 p.

2. Salo, Albert E., William L. Oaks, and Robert D. MacPhee. Measuring the Organic Carbon Content of Source Emissions for Air Pollution Control. Paper No. 74-190. (Presented at the 67th Annual Meeting of the Air Pollution Control Association. Denver, Colorado. June 9-13, 1974.) 25 p.

APPENDIX F

TABLES ON THE ECONOMIC IMPACTS OF THE ENERGY RECOVERY OPTION

TABLE F-2. LENGTH OF CONTROL PERIOD FOR AFFECTED CLOSED AND EXISTING LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
Average length of control period (years)	**69.6**	**50.8**	**36.0**
Distribution of affected landfills by length of control period (years)			
≤ 25	**213** (21)	**167** (51)	**39** (51)
26 to 50	**230** (22)	**49** (15)	**10** (13)
51 to 100	**310** (30)	**36** (11)	**27** (35)
101 to 150	**235** (23)	**51** (16)	**2** (3)
> 150	**36** (4)	**22** (7)	**0** (0.0)
Total	**1024** (100)	**325** (100)	**77** (100)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE F-1. SUMMARY INFORMATION FOR AFFECTED CLOSED AND EXISTING LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
Number of affected landfills	**1,024**	**325**	**77**
(Percent of total closed and existing landfills)	(14)	(5)	(1)
Distribution of affected landfills by design capacity (10^6 Mg)			
≤ 1	**470**	**126**	**14**
	(46)	(39)	(18)
1 to 5	**475**	**170**	**56**
	(46)	(52)	(73)
5 to 10	**62**	**24**	**2**
	(6)	(7)	(3)
> 10	**17**	**5**	**5**
	(2)	(2)	(6)
Total	**1,024**	**325**	**77**
	(100)	(100)	(100)
Privately owned affected landfills	**215**	**68**	**27**
(Percent of affected landfills)	(21)	(21)	(35)
Existing	**186**	**56**	**17**
Closed	**29**	**12**	**10**

Note: The numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE F-4. NET PRESENT VALUE OF ENTERPRISE COSTS FOR AFFECTED CLOSED AND EXISTING LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National enterprise costs (10^6)			
Capital	1,052	324	121
Operating	2,024	424	155
Energy Recovery Revenue	1,625	299	154
Total	1,450	450	123
Average total enterprise cost per affected landfill (10^6)	1.42	1.39	1.59
Distribution of affected landfills by net present value of enterprise costs (10^6)			
≤ 0.5	155	61	17
	(15)	(19)	(22)
0.5 to 1.0	179	70	17
	(18)	(22)	(22)
1.0 to 3.0	627	162	33
	(61)	(50)	(43)
3.0 to 5.0	63	32	10
	(6)	(10)	(13)
> 5.0	0	0	0
	(0)	(0)	(0)
Total	1,024	325	77
	(100)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of enterprise costs is calculated using a 4 percent discount rate for publicly owned landfills and an 8 percent discount rate for privately owned landfills. Details may not add to totals due to rounding.

TABLE F-3. LENGTH OF CONTROL PERIOD PRIOR TO CLOSURE FOR AFFECTED EXISTING LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
Average length of control period prior to closure (years)	20.9	14.5	8.6
Distribution of affected landfills by length of control period prior to closure (years)			
≤ 5	228 (28)	124 (49)	36 (57)
6 to 10	109 (13)	36 (14)	15 (24)
11 to 20	247 (30)	53 (21)	2 (3)
21 to 50	172 (21)	10 (4)	10 (16)
> 50	65 (8)	29 (12)	0 (0)
Total	821 (100)	252 (100)	63 (100)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding. Excludes closed landfills.

TABLE F-6. ANNUALIZED ENTERPRISE CONTROL COST PER HOUSEHOLD FOR AFFECTED EXISTING LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Level (Mg NMOC/yr)		
	25	**100**	**250**
National annualized cost per household ($/Household)	**9.50**	**15.47**	**8.33**
Distribution of affected landfills by annualized cost per household ($/Household)			
≤ 3.50	**138** (17)	**29** (12)	**17** (27)
3.50 to 7.00	**111** (14)	**24** (10)	**0** (0)
7.00 to 15.00	**182** (22)	**83** (33)	**32** (51)
15.00 to 30.00	**162** (20)	**58** (23)	**7** (11)
> 30.00	**228** (28)	**58** (23)	**7** (11)
Total	**821** (100)	**252** (100)	**63** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent from 1992 to the year of closure. Details may not add to totals due to rounding. Excludes closed landfills.

TABLE F-5. ANNUALIZED ENTERPRISE CONTROL COST PER Mg OF MSW FOR AFFECTED EXISTING LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Level (Mg NMOC/yr)		
	25	100	250
National annualized cost per Mg MSW ($/Mg MSW)	**1.64**	**2.66**	**1.43**
Distribution of affected landfills by annualized cost per Mg MSW ($/Mg MSW)			
≤ 0.50	**104** (13)	**29** (12)	**17** (27)
0.50 to 1.25	**153** (19)	**24** (10)	**0** (0)
1.25 to 3.00	**211** (26)	**90** (36)	**31** (49)
3.00 to 10.00	**259** (32)	**94** (37)	**15** (24)
> 10.00	**94** (11)	**15** (6)	**0** (0)
Total	**821** (100)	**252** (100)	**63** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent from 1992 to the year of closure. Details may not add to totals due to rounding. Excludes closed landfills.

TABLE F-8. SUMMARY INFORMATION FOR AFFECTED NEW LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
Number of affected landfills (Percent of total new landfills)	**140** (15)	**39** (4)	**10** (1)
Distribution of affected landfills by design capacity (10^6 Mg)			
≤ 1	**58** (41)	**0** (0)	**0** (0)
1 to 5	**73** (52)	**32** (82)	**3** (30)
5 to 10	**7** (5)	**7** (18)	**7** (70)
> 10	**2** (1)	**0** (0)	**0** (0)
Total	**140** (100)	**39** (100)	**10** (100)
Privately owned affected landfills (Percent of affected landfills)	**34** (24)	**0** (0)	**0** (0)

Note: The numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE F-7. NET PRESENT VALUE OF SOCIAL COSTS FOR AFFECTED CLOSED AND EXISTING LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National social costs (10^6)			
Capital	2,351	622	239
Operating	2,846	580	213
Energy Recovery Revenue	2,238	374	198
Total	2,958	828	253
Average total social cost per affected landfill (10^6)	2.89	2.55	3.27
Distribution of affected landfills by net present value of social costs (10^6)			
≤ 0.5	31	29	7
	(3)	(9)	(9)
0.5 to 1.0	95	29	10
	(9)	(9)	(13)
1.0 to 3.0	530	170	22
	(52)	(52)	(29)
3.0 to 5.0	269	53	14
	(26)	(16)	(18)
5.0 to 10.0	89	44	24
	(9)	(14)	(31)
> 10.0	10	0	0
	(1)	(0)	(0)
Total	1,024	325	77
	(100)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of social cost is computed using a two-step discounting procedure. First, capital costs are annualized at 10 percent over the control period. Then, present values are computed by discounting annual operating costs and annualized capital costs at 3 percent. Details may not add to totals due to rounding.

TABLE F-10. LENGTH OF CONTROL PERIOD PRIOR TO CLOSURE FOR AFFECTED NEW LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Levels (Mg NMOC/yr)		
	25	100	250
Average length of control period prior to closure (years)	**13.0**	**12.1**	**7.3**
Distribution of affected landfills by length of control period prior to closure (years)			
≤ 5	**29** (21)	**7** (18)	**3** (30)
6 to 10	**24** (17)	**0** (0)	**7** (70)
11 to 20	**73** (52)	**32** (82)	**0** (0)
21 to 50	**14** (10)	**0** (0)	**0** (0)
Total	**140** (100)	**39** (100)	**10** (100)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE F-9 LENGTH OF CONTROL PERIOD FOR AFFECTED NEW LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Levels (Mg NMOC/yr)		
	25	**100**	**250**
Average length of control period (years)	**65.0**	**56.2**	**75.2**
Distribution of affected landfills by length of control period (years)			
≤ 25	**24** (17)	**7** (18)	**3** (30)
26 to 50	**46** (33)	**15** (38)	**0** (0)
51 to 100	**36** (26)	**7** (18)	**7** (70)
101 to 150	**34** (24)	**10** (26)	**0** (0)
Total	**140** (100)	**39** (100)	**10** (100)

Note: Numbers in parentheses are percentages. Details may not add to totals due to rounding.

TABLE F-12. ANNUALIZED ENTERPRISE CONTROL COST PER Mg OF MSW FOR AFFECTED NEW LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Level (Mg NMOC/yr)		
	25	**100**	**250**
National annualized cost per Mg MSW ($/Mg MSW)	**0.95**	**0.92**	**0.59**
Distribution of affected landfills by annualized cost per Mg MSW ($/Mg MSW)			
≤ 0.25	**17** (12)	**0** (0)	**0** (0)
0.25 to 0.50	**10** (7)	**0** (0)	**0** (0)
0.50 to 1.00	**34** (24)	**10** (26)	**8** (80)
1.00 to 3.00	**43** (31)	**29** (74)	**2** (20)
> 3.00	**36** (26)	**0** (0)	**0** (0)
Total	**140** (100)	**39** (100)	**10** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent over the life of the landfill. Details may not add to totals due to rounding.

TABLE F-11. NET PRESENT VALUE OF ENTERPRISE COSTS FOR AFFECTED NEW LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National enterprise costs (10^6)			
Capital	86	64	32
Operating	181	110	48
Energy Recovery Revenue	116	112	62
Total	150	63	18
Average total enterprise cost per affected landfill (10^6)	1.07	1.61	1.83
Distribution of affected landfills by net present value of enterprise costs (10^6)			
≤ 0.5	53	0	0
	(38)	(0)	(0)
0.5 to 1.0	27	7	2
	(19)	(18)	(20)
1.0 to 3.0	53	25	8
	(38)	(64)	(80)
3.0 to 5.0	7	7	0
	(5)	(18)	(0)
>5.0	0	0	0
	(0)	(0)	(0)
Total	140	39	10
	(100)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of enterprise costs is calculated using a 4 percent discount rate for publicly owned landfills and an 8 percent discount rate for privately owned landfills. Details may not add to totals due to rounding.

TABLE F-14. NET PRESENT VALUE OF SOCIAL COSTS FOR AFFECTED NEW LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
National social costs (10^6)			
Capital	**261**	**146**	**77**
Operating	**326**	**151**	**69**
Energy Recovery Revenue	**278**	**155**	**88**
Total	**309**	**142**	**58**
Average total social cost per affected landfill (10^6)	**2.20**	**3.68**	**5.95**
Distribution of affected landfills by net present value of social costs (10^6)			
≤ 0.5	**0**	**0**	**0**
	(0)	(0)	(0)
0.5 to 1.0	**24**	**0**	**0**
	(17)	(0)	(0)
1.0 to 3.0	**82**	**22**	**2**
	(59)	(56)	(20)
3.0 to 5.0	**27**	**10**	**0**
	(19)	(26)	(0)
> 5.0	**7**	**7**	**8**
	(5)	(18)	(80)
Total	**140**	**39**	**10**
	(100)	(100)	(100)

Note: Numbers in parentheses are percentages. Net present value of social cost is computed using a two-step discounting procedure. First, capital costs are annualized at 10 percent over the control period. Then, present values are computed by discounting annual operating costs and annualized capital costs at 3 percent. Details may not add to totals due to rounding

TABLE F-13. ANNUALIZED ENTERPRISE CONTROL COST PER HOUSEHOLD FOR AFFECTED NEW LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Level (Mg NMOC/yr)		
	25	**100**	**250**
National annualized cost per household ($/Household)	**5.53**	**5.36**	**3.41**
Distribution of affected landfills by annualized cost per household ($/Household)			
≤ 0.75	**10** (7)	**0** (0)	**0** (0)
0.75 to 1.50	**7** (5)	**0** (0)	**0** (0)
1.50 to 3.00	**10** (7)	**0** (0)	**8** (80)
3.00 to 10.00	**48** (34)	**39** (100)	**2** (20)
> 10.00	**65** (46)	**0** (0)	**0** (0)
Total	**140** (100)	**39** (100)	**10** (100)

Note: Numbers in parentheses are percentages. Costs for publicly owned landfills are annualized at 4 percent over the control period. Costs for privately owned landfills are annualized at 8 percent over the life of the landfill. Details may not add to totals due to rounding.

TABLE F-16. COST EFFECTIVENESS FOR AFFECTED CLOSED AND EXISTING LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Level (Mg NMOC/yr)		
	25	100	250
National cost effectiveness ($/Mg NMOC)	**1,449**	**719**	**433**
Distribution of affected landfills by cost effectiveness ($/Mg NMOC)			
≤ 1,000	**157** (15)	**189** (58)	**68** (88)
1,000 to 2,000	**269** (26)	**102** (31)	**7** (9)
2,000 to 5,000	**414** (41)	**7** (2)	**0** (0)
5,000 to 10,000	**143** (14)	**12** (4)	**2** (3)
> 10,000	**41** (4)	**15** (5)	**0** (0)
Total	**1,024** (100)	**325** (100)	**77** (100)
Incremental cost effectiveness	**2,287**	**989**	**—**

Note: Numbers in parentheses are percentages. Cost effectiveness is calculated by dividing the net present value of social cost by the discounted NMOC emission reduction (see Tables F-7 and F-15). Details may not add to totals due to rounding.

TABLE F-15. NET PRESENT VALUE OF EMISSIONS REDUCTIONS FOR AFFECTED CLOSED AND EXISTING LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
Undiscounted NMOC emission reduction (10^6 Mg)	5.81	3.06	1.26
Discounted NMOC emission reduction (10^6 Mg)	2.04	1.15	0.59
Average discounted NMOC emission reduction per affected landfill (Mg)	1,993	3,546	7,560
Distribution of affected landfills by discounted NMOC emission reduction per affected landfill (Mg)			
≤ 1,000	429 (42)	82 (25)	17 (22)
1,000 to 2,000	305 (30)	94 (29)	0 (0)
2,000 to 5,000	208 (20)	94 (29)	22 (29)
5,000 to 10,000	58 (6)	29 (9)	14 (18)
> 10,000	24 (2)	24 (8)	24 (31)
Total	1,024 (100)	324 (100)	77 (100)

Note: Numbers in parentheses are percentages. Net present value of emission reductions is calculated using a 3 percent discount rate. Details may not add to totals due to rounding.

TABLE F-18. COST EFFECTIVENESS FOR AFFECTED NEW LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

	Stringency Level (Mg NMOC/yr)		
	25	100	250
National cost effectiveness ($/Mg NMOC)	1,244	963	891
Distribution of affected landfills by cost effectiveness ($/Mg NMOC)			
≤ 1,000	24 (17)	15 (38)	7 (70)
1,000 to 2,000	53 (38)	24 (64)	3 (30)
2,000 to 5,000	39 (28)	0 (0)	0 (0)
5,000 to 10,000	17 (12)	0 (0)	0 (0)
> 10,000	7 (5)	0 (0)	0 (0)
Total	140 (100)	39 (100)	10 (100)
Incremental cost effectiveness	1,661	870	—

Note: Numbers in parentheses are percentages. Cost effectiveness is calculated by dividing the net present value of social cost by the discounted NMOC emission reduction (see Tables F-14 and F-17). Details may not add to totals due to rounding.

TABLE F-17. NET PRESENT VALUE OF EMISSIONS REDUCTIONS FOR AFFECTED NEW LANDFILLS: COST-MINIMIZING OPTION AT LANDFILLS WITH POSITIVE ENERGY RECOVERY COSTS

Net Present Value	Stringency Levels (Mg NMOC/yr) 25	100	250
Undiscounted NMOC emission reduction (10^6 Mg)	0.83	0.49	0.25
Discounted NMOC emission reduction (10^6 Mg)	0.25	0.15	0.06
Average discounted NMOC emission reduction per affected landfill (Mg)	1,765	3,818	6,680
Distribution of affected landfills by discounted NMOC emission reduction per affected landfill (Mg)			
≤ 1,000	77 (55)	0 (0)	0 (0)
1,000 to 2,000	17 (12)	7 (18)	2 (20)
2,000 to 5,000	39 (28)	25 (64)	0 (0)
> 5,000	7 (5)	7 (18)	8 (80)
Total	140 (100)	39 (100)	10 (100)

Note: Numbers in parentheses are percentages. Net present value of emission reductions is calculated using a 3 percent discount rate. Details may not add to totals due to rounding.

APPENDIX G

THEORETICAL COLLECTION SYSTEM DESIGN

APPENDIX G

THEORETICAL COLLECTION SYSTEM DESIGN

G.1 INTRODUCTION

This appendix provides the theoretical approach for designing landfill gas collection systems. Design equations for active vertical wells, active horizontal trenches, and passive vertical wells are detailed in Sections G.3, G.4, and G.5, respectively. These equations were used in Chapters 5, 6, and 7 to quantify the nationwide impact of controlling landfills and as the foundation for the collection system design procedure outlined in Chapter 9. The design procedure in Chapter 9 is a graphical interpretation of the theoretical design equation. The derivation of this procedure, is provided in Section G.6.

G.2 ASSUMPTIONS

The following assumptions have been made in developing the design equations for landfill gas collection systems:

- The design of the active vertical and passive collection systems is based on the peak landfill gas generation rate which is calculated using: (1) an equation that describes the radius of influence of extraction wells and (2) site-specific information for each landfill (e.g., amount of refuse in place, landfill depth, landfill age, acceptance rate, etc.).
- Scholl Canyon Model, a first order decay model described in Chapter 3, is used to estimate the landfill gas generation rate.
- The lag time (typically less than one to two years) for the landfill gas generation is negligible when compared to the total life of landfill gas generation. Thus, the peak landfill gas generation rate is assumed to occur at the time of closure.

G.3 THEORETICAL APPROACH FOR ACTIVE VERTICAL WELL COLLECTION SYSTEM DESIGN

The geometry of an active well system is illustrated in Figure G-1. The radius of influence for a vertical well can be obtained by the following mass balance equation:

$$R_a = (Q_{w,a} \text{ Design Capacity}/\pi L \rho_{refuse} Q_{gen} E_a)^{1/2} \quad (1)$$

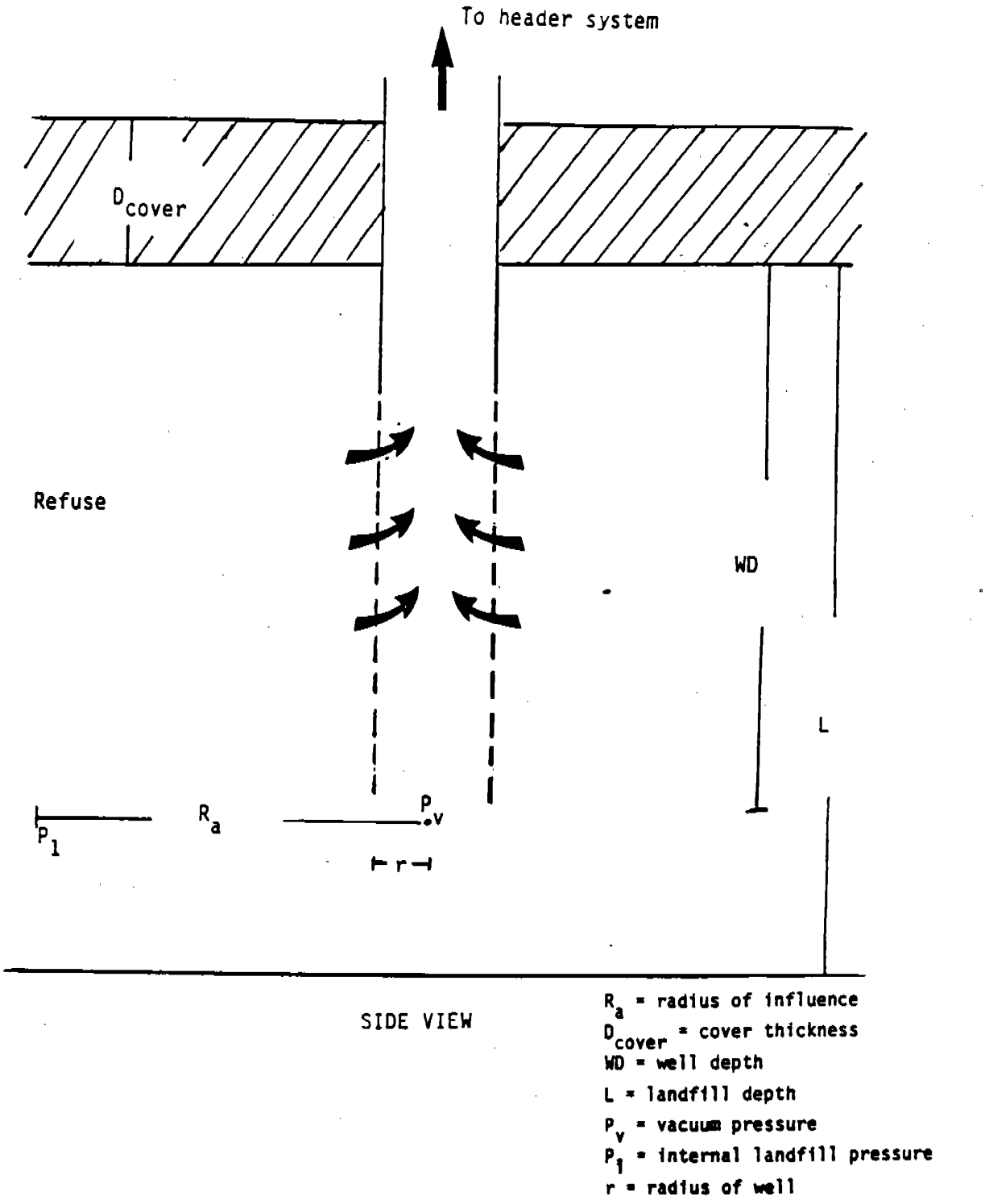


Figure G-1. Model active vertical well collection system geometry.

where,

R_a = radius of influence for active collection systems, m

$Q_{w,a}$ = landfill gas flowrate per well, m^3/sec

Design Capacity = design capacity of the landfill, kg

π = 3.14

refuse = refuse density, kg/m^3

L = landfill depth, m

Q_{gen} = peak landfill gas generation rate, m^3/sec

E_a = fractional collection efficiency of active well systems

Equation (1) calculates the radius of influence based on the maximum landfill gas generation rate (Q_{gen}) and the collection efficiency of the active vertical well system (E_a). If the lag time for landfill gas generation is neglected, Q_{gen} is assumed to occur at the time of landfill closure and can be determined using the Scholl Canyon model:

$$Q_{gen} = 2 \ L_o \ R \ (1 - \exp(-kt)) \qquad (2)$$

where,

Q_{gen} = peak landfill gas generation rate, m^3/yr

L_o = refuse methane generation potential, m^3 methane/Mg refuse

R = average refuse acceptance rate, Mg/yr

k = landfill gas generation rate constant, 1/yr

t = landfill age upon closure

To calculate Q_{gen} using Equation (2), it is necessary to know values for L_o and k. As discussed above, L_o and k vary from landfill to landfill depending on the composition, moisture content, pH, and internal landfill temperature. Values of L_o and k have been determined empirically for a total of 54 landfills based on test well data and/or data from existing landfill gas collecting systems.[1] For these landfills, the estimated L_o and k correspond to the collected landfill gas flowrate

(Q_{gen} x E_a) rather than the total landfill gas generation rate. Using the values of L_o and k derived in this way, the product of Q_{gen} and E_a may be calculated using the following equation:

$$Q_{gen}\ E_a = 2\ L'_o\ R\ [1 - \exp\ (-k't)] \qquad (3)$$

where,

L'_o = refuse methane generation potential estimated from test well data and/or existing landfill gas collection system, m^3 methane/Mg refuse.

k' = landfill gas generation rate constant estimated from test well data and/or existing landfill gas collection system, 1/yr

Once the radius of influence is calculated, the number of wells necessary can be calculated from the landfill area.

$$n = A/(\pi R_a^{\ 2}) \qquad (4)$$

where,

n = number of wells
A = area of landfill, m^2
= design capacity/(refuse density X depth)
R_a = radius of influence, m
π = 3.14

From Darcy's Law, the landfill pressure corresponding to the calculated radius of influence, refuse permeability, the magnitude of vacuum applied, and the collectable landfill gas flowrate (i.e. Q_{gen} X E_a) can be calculated.[2]

$$\frac{P_l^{\ 2} - P_v^{\ 2}}{P_v} = \frac{R_a^{\ 2}\ \ln(R_a/r)\,\mu_{lfg}\ \ _{refuse}\ (Q_{gen}\ E_a)}{\text{Design Capacity}\ k_{refuse}\ (WD/L)} \qquad (5)$$

where,

P_l = internal landfill pressure, Newton/m^2
P_v = vacuum pressure, Newton/m^2

R_a = radius of influence, m

r = radius of outer well (or gravel casing), m

ρ_{refuse} = refuse density, 650 kg/m^3

k_{refuse} = intrinsic refuse permeability, m^2

μ_{lfg} = landfill gas viscosity, Newton-sec/m^2

Design Capacity = design capacity of landfill, kg

WD = well depth (i.e., 0.75L), m

L = landfill depth, m

Q_{gen} = peak landfill gas generation rate, ft^3/yr

E_a = fractional collection efficiency of active well system

Once the radius of influence and the number of wells are calculated, it is necessary to check if significant air infiltration exists under the given refuse permeability, cover permeability, and vacuum applied.

The flow of air through the cover material is illustrated in Figure G-2. At steady state, the flowrate through the interface of atmosphere and the cover material, and the flowrate through the interface of cover material and the refuse are the same. Thus, the following equation is obtained at steady state:

$$v_{air} = k_{cover} (P_{atm} - P_i)/(\mu_{air} D_{cover}) = k_{refuse,v} (P_i - P_v)/(\mu_{air} X) \quad (6)$$

where,

v_{air} = air velocity through cover and refuse, m/sec

k_{cover} = intrinsic cover permeability, m^2

P_{atm} = atmospheric pressure, Newton/m^2

P_i = interface pressure, Newton/m^2

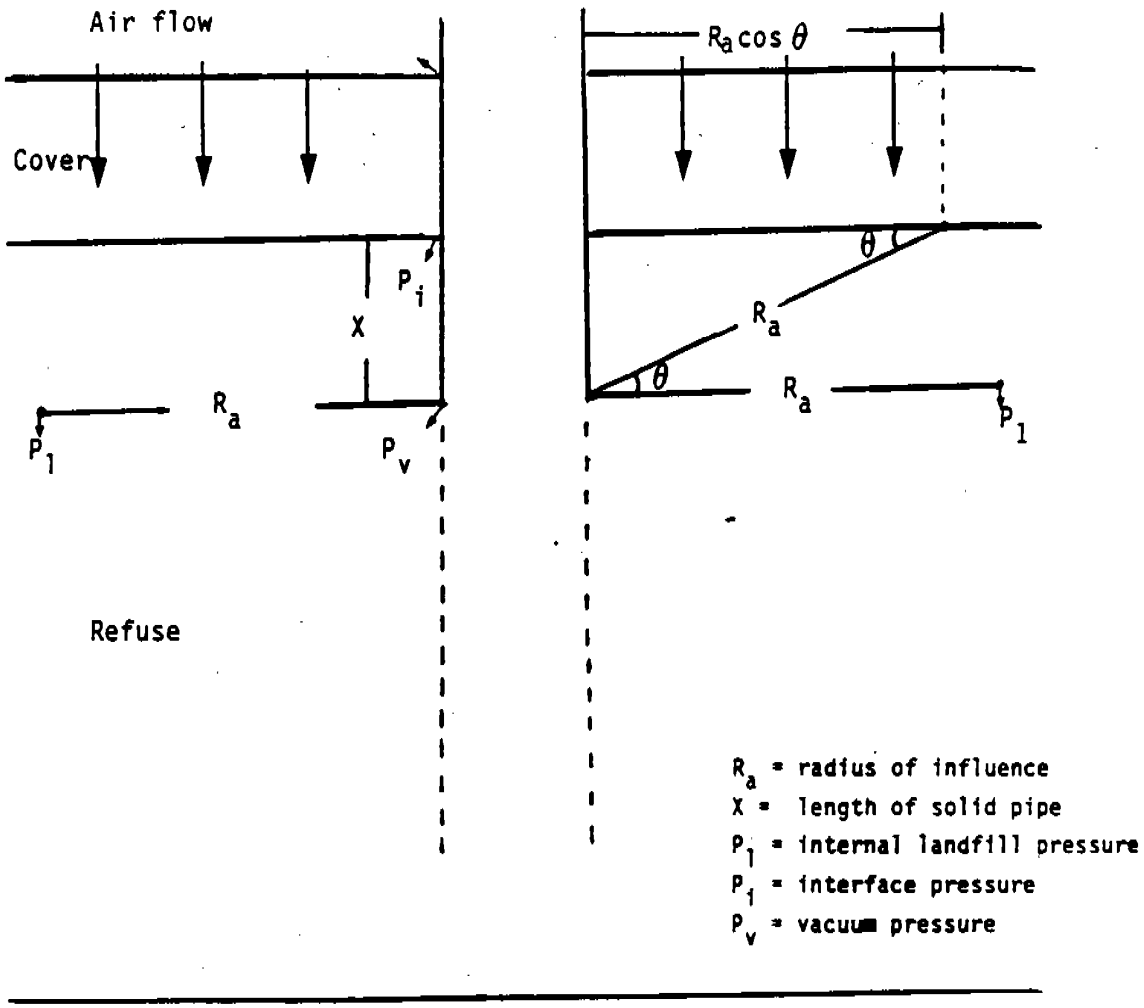
μ_{air} = air viscosity, Newton-sec/m^2

D_{cover} = cover thickness, m

$k_{refuse,v}$ = intrinsic vertical refuse permeability, Newton-sec/m^2

P_v = vacuum pressure, Newton/m^2

X = length of solid pipe, m



SIDE VIEW

Figure G-2. Air flow through landfill cover.

It should be noted that the vertical refuse permeability is used for air infiltration equations rather than the horizontal permeability (or simply permeability). According to industry experts, the horizontal permeability is approximately 10 times greater than the vertical permeability due to the layering effect of the refuse accumulation.[3]

The flowrate of air can be calculated using the following equation:

$$Q_{air} = (v_{air})\ (R_a \cos(\theta))^2$$
$$= v_{air}\ R_a^2\ (\text{if } \theta = -0) \qquad (7)$$

If the maximum allowable percent of oxygen in the total collected landfill gas is assumed to be 0.5 percent, the corresponding allowable percent of air in landfill gas is 2.44 percent.[4] Therefore, the minimum solid pipe length required (X) can be calculated by the following equation:

$$(0.0244)(Q_{gen}\ E_a) = k_{cover}\ (P_{atm} - P_i)\ A/(\mu_{air}\ D_{cover}) \qquad (8)$$
$$= k_{refuse,v}\ (P_i - P_v)\ A\ /(\mu_{air}\ X)$$

Note that Equation (8) only accounts for the air infiltration from the surface of a landfill (i.e, the air infiltration from the sides of landfill is negligible compared to the air infiltration from the surface of landfill). Equation (8) can be simplified to:

$$X = \{[k_{refuse,v}\ k_{cover}\ (P_{atm} - P_v)\ A/\mu_{air}\ (0.0244)(Q_{gen}\ E_a)] - k_{refuse,v}\ D_{cover}\}/k_{cover} \qquad (9)$$

If the required solid pipe length is greater than the available solid pipe length (based on the given landfill depth), the landfill is considered shallow and the magnitude of vacuum needs to be reduced to meet the 2.44 percent air content requirement. The available solid pipe length can be estimated by assuming that the well depth is 75 percent of the landfill depth and two thirds of the well depth needs to be perforated and one third of the

well needs to be solid.[5] For shallow landfills, the magnitude of vacuum required can be calculated using Equation (9) by setting X to be the available solid pipe length.

The radius of influence is then recalculated based on the new vacuum and the landfill pressure calculated using Equation (5). The radius of influence for shallow landfills is expected to be smaller since the pressure driving force (or pressure gradient) would be less. Thus, to achieve the same collection efficiency in a shallow landfill as in a deeper landfill, the number of wells required in a shallow landfill will be larger.

The design calculation steps for active vertical well collections systems are illustrated in Figure G-3.

G.4 THEORETICAL APPROACH FOR HORIZONTAL TRENCH COLLECTION SYSTEMS DESIGN

The geometry of a model horizontal trench system is illustrated in Figure G-4. The governing equations for horizontal trench systems are also based on a mass balance equation and Darcy's Law. The basic approach for designing horizontal trench collection systems is to use the radius of influence calculated for active vertical wells (using Equation (1)) to determine the horizontal spacing between trenches, since the radius of influence is a function of the refuse permeability and the landfill pressure. The landfill pressure, in turn, is a function of the landfill gas generation rate and degree of containment (i.e., type of liner, etc.). The vertical spacing between the trench layers can be calculated by the following equations using vertical refuse permeability.

$$R_v^2 \ln(R_v/r) = [(P_1^2 - P_v^2)\ \text{Design Capacity}\ k_{refuse,v}\ (WD/L)]/ \quad (11)$$
$$[P_v\ \mu_{LFG\ refuse}\ (Q_{gen}\ E_a)]$$

$$S_v = 2\ R_v$$

where,

P_1 = internal landfill pressure, Newton/m^2

P_v = average vacuum pressure along the trench length, Newton/m^2

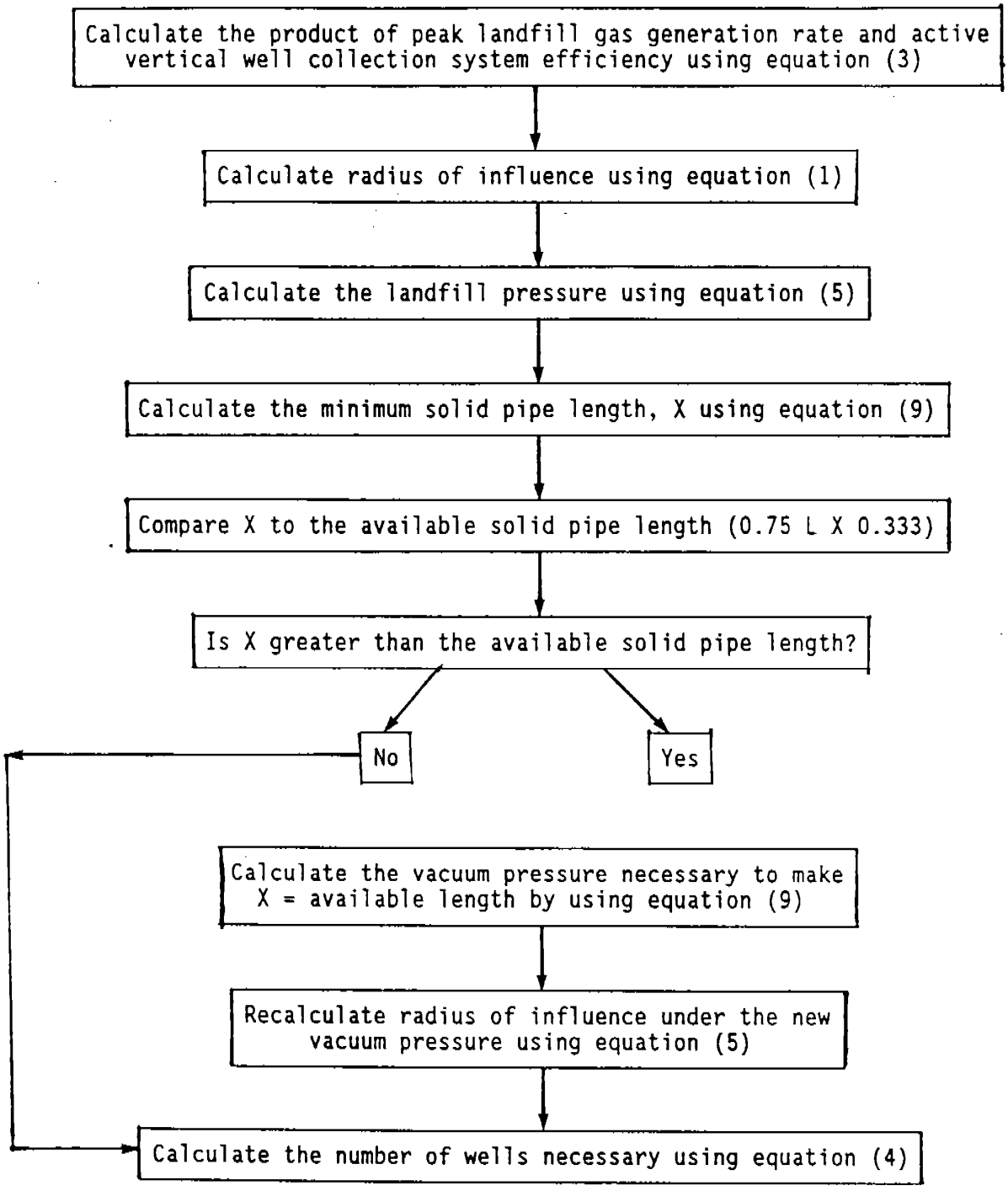


Figure G-3. Active vertical well collection system design calculation steps.

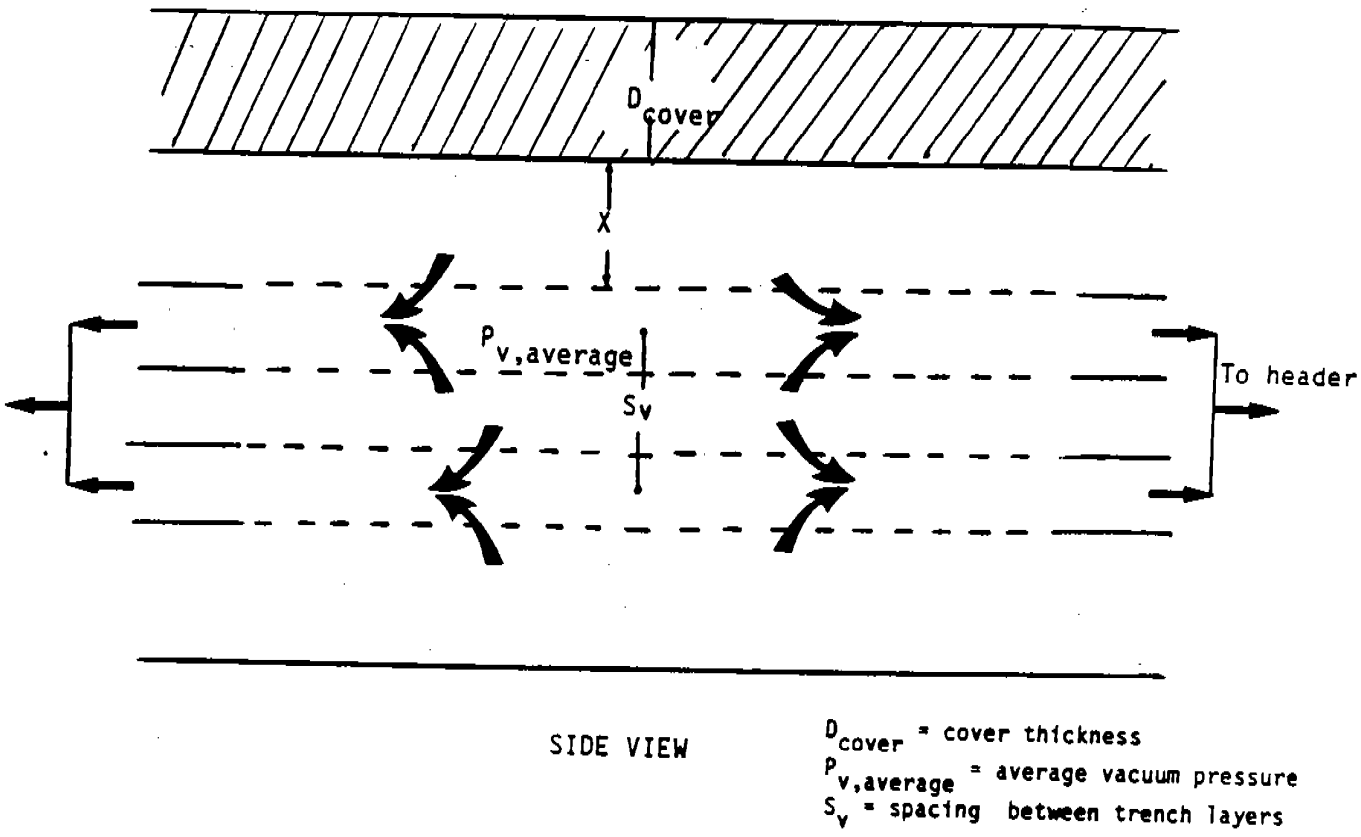


Figure G-4. Model horizontal trench system geometry.

S_v = vertical spacing between trench layers (i.e., radius of influence for vertical direction), m

R_v = vertical radius of influence, m

r = radius of gravel casing, m

$_{refuse}$ = refuse density, 650 kg/m^3

μ_{lfg} = landfill gas viscosity, Newton-sec/m^2

$k_{refuse,v}$ = intrinsic vertical refuse permeability, m^2

Design Capacity = design capacity of landfill, kg

WD = well depth, m (typically 0.75 L)

L = landfill depth, m

Q_{gen} = peak landfill gas generation rate, m^3/yr

E_a = fractional collection efficiency of active well system

Note that the vacuum pressure used in Equation (11) is an average vacuum pressure along the length of a trench. If the vacuum is pulled only at one end of a trench, there may be a significant pressure drop along the length of the trench unless the collected gas flowrate is too small to yield a significant pressure drop. The pressure drop can be minimized if vacuum is pulled evenly using a manifold system.

The number of trench layers can be calculated by:

$$n_l = L/S_v \qquad (12)$$

where,

n_l = number of trench layers

L = landfill depth, m

S_v = vertical spacing between trenches, m

Once the vertical spacing between the trench layers is calculated, the horizontal spacing between trenches can be calculated by the following equations:

$$R_h^2 \ln(R_h/r) = [(P_l^2 - P_v^2)\ \text{Design Capacity}\ k_{refuse,h}\ (WD/L)]/ [P_v\ \mu_{lfg}\ \rho_{refuse}\ (Q_{gen}\ E_a)] \quad (13)$$

$$S_h = 2\ R_h$$

where,

P_l = internal landfill pressure, Newton/m^2

P_v = average vacuum pressure along the trench length, Newton/m^2

R_h = horizontal radius of influence, m

S_h = horizontal spacing between trench layers, m

r = radius of gravel casing, m

μ_{lfg} = landfill gas viscosity, Newton-sec/m^2

ρ_{refuse} = refuse density, 650 kg/m^3

$k_{refuse,h}$ = intrinsic horizontal refuse permeability, m^2

Design Capacity = design capacity of landfill, kg

WD = well depth, m (typically 0.75 L)

L = landfill depth, m

Q_{gen} = peak landfill gas generation rate, m^3/yr

E_a = fractional collection efficiency of active well system

Assuming that the landfill is square, the number of trenches per trench layer can be calculated by:

$$n_t = A^{1/2} / S_h \quad (14)$$

where,

n_t = number of trenches per trench layer

A = landfill area, m^2

S_h = horizontal spacing between trenches, m

Therefore, the total required trench length for a square landfill is:

$$L_t = n_t \, n_l \, A^{1/2} \tag{15}$$

where,

L_t = total length of trench, m
A = landfill area, m^2

The air infiltration equations for the active vertical collection systems also apply to the horizontal trench collection systems. If the landfill is shallow, the radii of influence for vertical and horizontal directions are calculated (for active vertical well systems) using the reduced magnitude of vacuum and they are applied to horizontal trench systems as the vertical and horizontal spacings.

The design calculation steps for horizontal trench collection systems are presented in Figure G-5.

G.5 THEORETICAL APPROACH FOR PASSIVE COLLECTION SYSTEMS DESIGN

The geometry of the model passive well system is illustrated in Figure G-6. The governing equations for active systems also apply to passive systems except that the pressure gradient in Equation (5) is based on the difference in landfill pressure and atmospheric pressure as follows:

$$\frac{P_l^2 - P_{atm}^2}{P_{atm}} = \frac{R_p^2 \ln(R_p/r) \, \mu_{lfg} \, \rho_{refuse} \, (Q_{gen} \, E_p)}{\text{Design Capacity} \; k_{refuse} \, (WD/L)} \tag{16}$$

where,

P_l = internal landfill pressure, Newton/m^2
P_{atm} = atmospheric pressure, Newton/m^2
R_p = radius of influence for passive system, m
r = radius of outer well (or gravel casing), m
$_{refuse}$ = refuse density, 650 kg/m^3
k_{refuse} = intrinsic refuse permeability, m^2
μ_{lfg} = landfill gas viscosity, Newton-sec/m^2

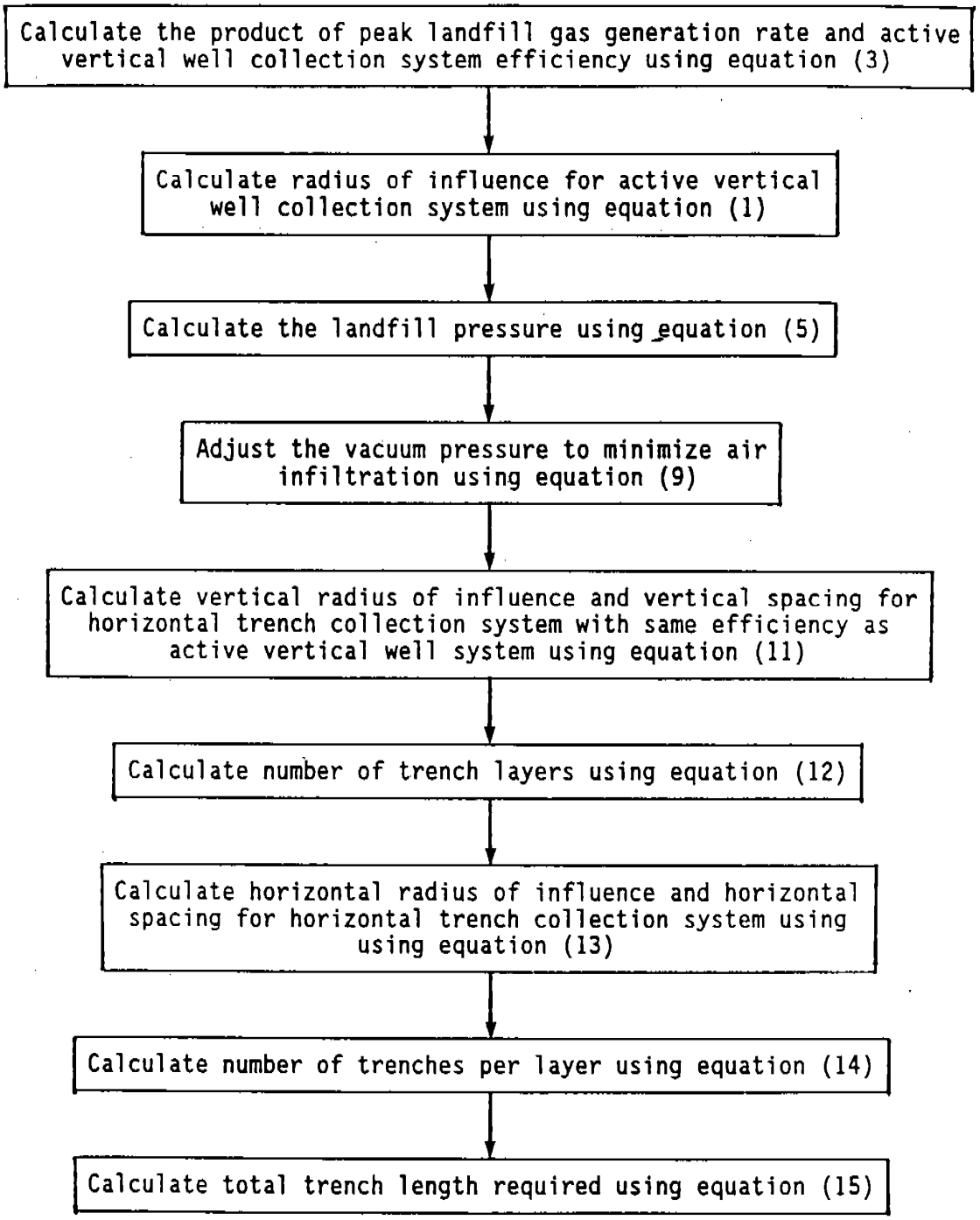
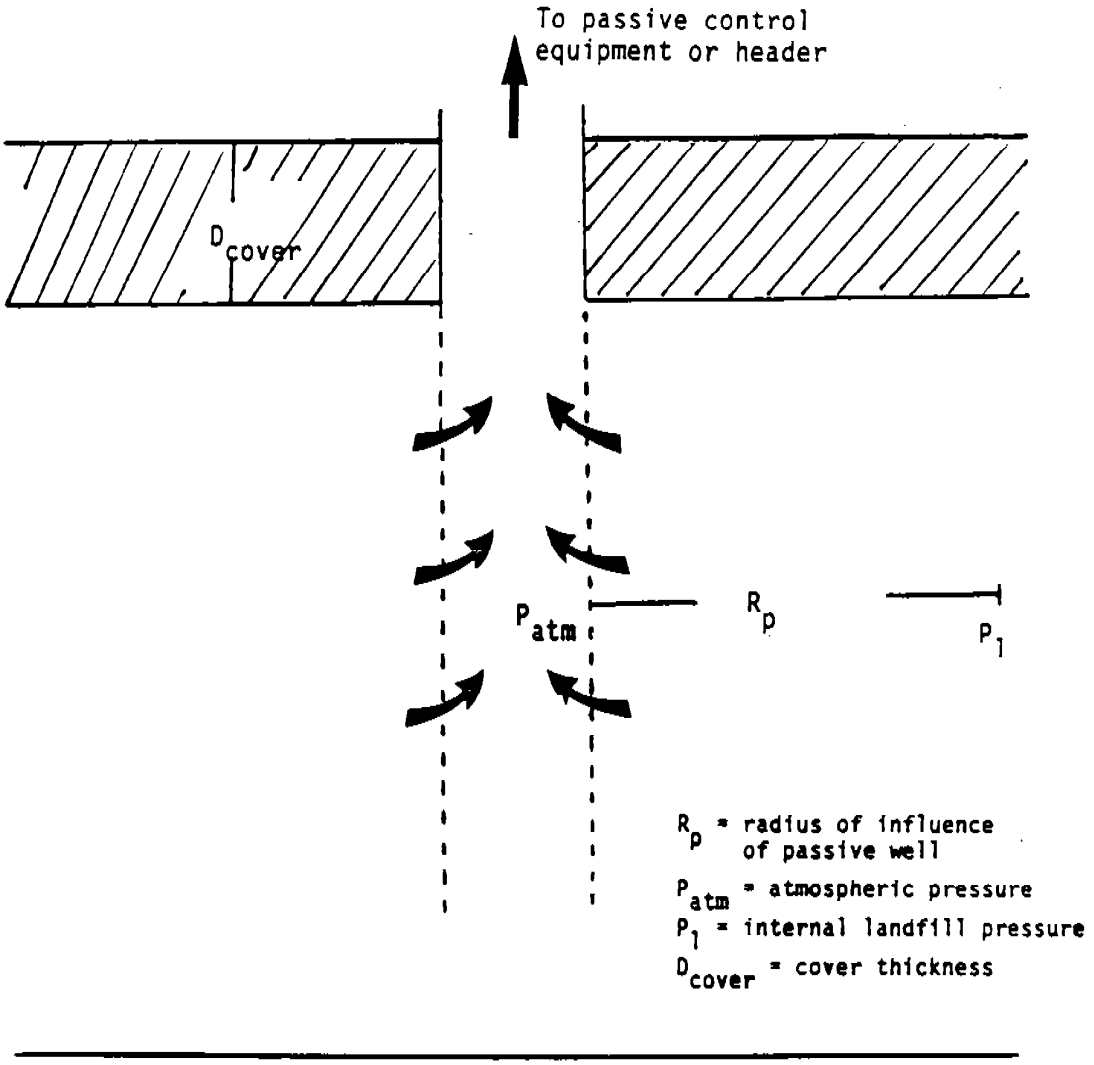


Figure G-5. Horizontal trench system design calculation steps.



SIDE VIEW

Figure G-6. Model passive collection system geometry.

Q_{gen} = peak landfill gas generation rate, m^3/yr

E_a = fractional collection efficiency of passive well system

Design Capacity = design capacity of landfill, kg

WD = well depth, m (typically 0.75 L)

L = landfill depth, m

The ratio of the radius of influence of passive systems to the radius of influence of active systems can be expressed by the following equation:

$$\frac{R_p^2 \ln(R_p/r)}{R_a^2 \ln(R_a/r)} = \frac{[(P_1^2 - P_{atm}^2)/P_{atm}]\ E_a}{[(P_1^2 - P_v^2)/P_v]\ E_p} \qquad (17)$$

By setting the ratio of collection efficiencies on passive systems and active systems to one, the passive system design needed to achieve the same collection efficiency as an active system can be determined. Based on the radius of influence of the passive wells obtained from Equation (17) the number of passive wells necessary can be calculated as follows:

$$n = A/(\pi R_p^2) \qquad (18)$$

where,

n = number of wells

A = landfill area, m^2

R_p = radius of influence for passive system, m

As discussed earlier, the problem of air infiltration does not exist for passive systems since the passive systems rely on the natural pressure gradient. The design calculation steps for passive collection systems are illustrated in Figure G-7.

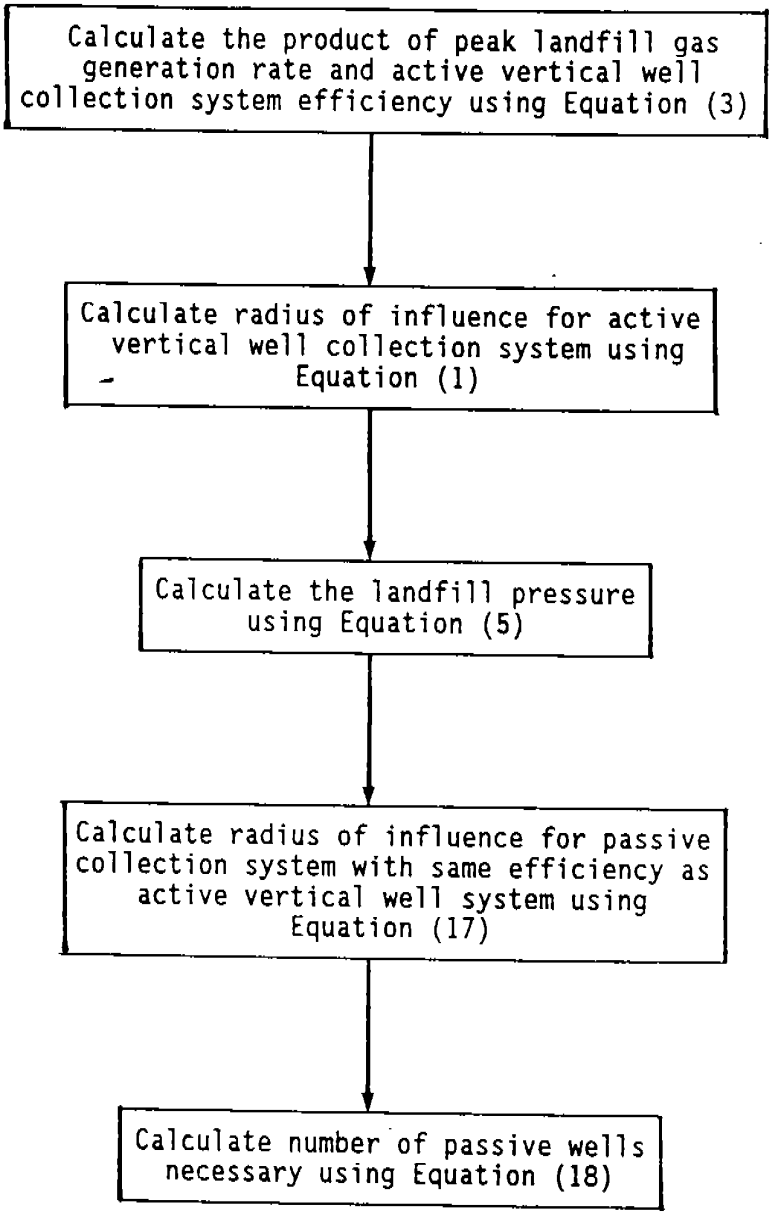


Figure G-7. Passive collection system design calculation steps.

G.6 GRAPHICAL INTERPRETATION OF THE THEORETICAL APPROACH

A graphical interpretation of the design equations provided in the previous sections was performed to simplify the approach landfill owners would have to take to design collection systems in the absence of site-specific data. Sections G.6.1 and G.6.2 describe the derivation of the simplified design approach for active collection systems and passive collection systems, respectively.

G.6.1 Simplified Approach for Active Collection System Design

The approach outlined in Chapter 9 for active collection systems is a two step process. The first step is to determine the maximum blower vacuum allowed for a given landfill depth. From Equation 9 in Section G.3, a relationship between the blower vacuum (P_v) and the landfill depth (L) was obtained.

- Derivation of P_v as a function of L

  Given: Equation 9

$$x = \frac{\dfrac{(k_{refuse,v})(k_{cover})(P_{atm} - P_v)\,A}{\mu_{air}\ .0244\ Q_{gen}} - (k_{refuse,v})(D_{cover})}{k_{cover}}$$

  From the well specifications, x, the length of solid pipe, is equal to 1/3 the well depth which is 75 percent of the landfill depth.

$$\therefore\ .25L = \frac{\dfrac{(k_{refuse,\ v})(k_{cover})(P_{atm} - P_v)\,A}{\mu_{air}\ .0244\ Q_{gen}} - (k_{refuse,v})(D_{cover})}{k_{cover}}$$

  Solving for P_v:

$$P_v = P_{atm} - [(.25L)(k_{cover}) + (k_{refuse})(D_{cover})] * (Q_{gen}/A)(.0244/k_{cover})(\mu_{air}/k_{refuse})$$

  But A can be expressed in terms of L

$$A = \frac{DC}{\rho_{refuse} L}$$

where,

L = Landfill depth, m
DC = Design Capacity, Mg
$_{refuse}$ = refuse density, kg/m^3

$$\therefore P_v = P_{atm} - [(.25L)(k_{cover}) + (k_{refuse})(D_{cover})] * (Q_{gen/DC})(\ _{refuse}L)(.0244/k_{cover})(\ _{air}/k_{refuse})$$

Using the following values for refuse density, refuse permeability, and air viscosity:

$$_{refuse} = 650 \text{ kg/m}^3$$
$$k_{refuse} = 3.743 \times 10^{-13} \text{ m}^2$$
$$_{air} = 1.8 \times 10^{-5} \text{ N-sec/m}^2$$

and assuming atmospheric pressure is equal to 1 atm, the equation becomes:

$$P_v = 1 - [(.25L)(k_{cover}) + (D_{cover})(3.743 \times 10^{-13})] * (Q_{gen}/DC)(L/k_{cover})(.004)$$

The ratio of Q_{gen} to DC will vary from landfill to landfill due to differences in active life and refuse composition. For the sake of simplicity, however, a single conservative value of this ratio was developed and used to generate a relationship between P_v and L that would apply to a wide variety of landfills. The OSW database of municipal landfills served as the source for values of Q_{gen}/DC. The Scholl Canyon model for landfill gas generation (Equation 2) was used to determine the maximum expected landfill gas flowrate for each landfill in the database. In order to obtain consistency in the landfill gas generation rate between landfills, a value of 0.02 1/yr was used for k, the gas generation rate constant, and a value of 230 m^3 methane/Mg refuse was used for L_o, the gas generation potential. These values represent the 80th percentile of the k's and L_o's that were randomly assigned to the landfills in the database to obtain national and economic impacts. More information on k and L_o is provided in Chapter 3.

The resulting values of Q_{gen}/DC ranged from .000025 cfm/Mg to .0007 cfm/Mg. The average was assumed to provide a reasonable, yet conservative value for Q_{gen}/DC that could apply to a wide range of landfills. Using this value of Q_{gen}/DC, the relationship between P_v and L was obtained for three types of caps: synthetic, clay, and soil. Using cover permeabilities and thicknesses provided in Table G-1, the following equations were developed for the three cover types:

Synthetic: $P_v = 1 - (4.2 \times 10^{-7} L^2 + 4.7 \times 10^{-4} L)$

TABLE G-1. COVER PERMEABILITIES AND THICKNESSES

Cover type	Permeability (m^2)	Thickness (m)	Reference
Synthetic	1.0×10^{-18}	7.6×10^{-4}	6
Clay	5.0×10^{-15}	.61	7
Soil	1×10^{-14}	.61	8

$$\text{Clay:}\quad P_v = 1 - (4.2 \times 10^{-7}\, L^2 + 7.6 \times 10^{-5}\, L)$$

$$\text{Soil:}\quad P_v = 1 - (4.2 \times 10^{-7}\, L^2 + 3.8 \times 10^{-5}\, L)$$

These equations are illustrated in Figure 9-6 in Chapter 9.

The second step in designing an active landfill gas collection system is to determine the radius of influence that corresponds to the maximum blower vacuum determined in the first step. From Equation 5 in Section G.3, a relationship between radius of influence for an active system (R_a) and blower vacuum (P_v) can be obtained.

- Derivation of R_a as a function of Pv.

  Given Equation 5

  $$\frac{P_1^2 - P_v^2}{P_v} = \frac{R_a^2\,(\ln(R_a/r)}{DC} \frac{LFG_{refuse}\, Q_{gen}}{k_{refuse}\,(WD/L)}$$

  Solving for R_a

  $$R_a^2 \ln (R_a/r) = \frac{P_1^2 - P_v^2}{P_v} \frac{DC}{Q_{gen}} \frac{k_{refuse}\,(WD/L)}{LFG_{refuse}}$$

  Using the following values:

  $$r = .3048 \text{ m}$$
  $$k_{refuse} = 3.743 \times 10^{-13}\ m^2$$
  $$WD/L = 0.75$$
  $$LFG_{refuse} = 1.15 \times 10^{-5}\ \text{N-sec/m}^2$$
  $$= 650\ \text{kg/m}^3$$

  the expression becomes

  $$R_a^2 \ln(R_a/.3048) = \frac{P_1^2 - P_v^2}{P_v} \frac{DC}{Q_{gen}}\ 8.06$$

  Using the average value of Q_{gen}/DC provided in the derivation of P_v as a function L and assuming a landfill gas pressure of 1.01 atm, the expression becomes

  $$R_a^2 \ln(R_a/.3048) = (1.02 - P_v^2/P_v)(1.7 \times 10^4)$$

  This equation is illustrated in Figure 9-7 in Chapter 9.

As mentioned in Chapter 9 using this approach to collection system design may result in an excessive number of wells when compared to the recommended empirical approach.

G.6.2 Simplified Approach for Passive Collection System Design

The approach outlined in Chapter 9 for passive collection systems is to determine the appropriate radius of influence for a given pressure drop across the collection and control device. The initial step in formulating this correlation was to develop a relationship between the radius of influence for a passive system (R_p) and the landfill gas pressure (P_l).

- Derivation of R_p as a function of P_l

  From Equation 17

  $$\frac{Rp^2 \ln(Rp/r)}{Ra^2 \ln(Ra/r)} = \frac{[(P_l^2 - P_{atm}^2)/P_{atm}]\ Ep}{[(P_l^2 - P_v^2)/P_v]\ Ea}$$

  Assume the collection efficiencies of an active collection system and a passive collection system are equal (i.e., Ep/Ea = 1) and solve for Rp.

  From Equation 5

  $$\frac{Ra^2 \ln(R/r)}{[(P_l^2 - P_v^2)/P_v]} = (DC/Q_{gen})\ K_{refuse}\ (WD/L)_{LFG}^{refuse}$$

  $$\therefore\ Rp^2 \ln(Rp/r) = \frac{P_l^2 - P_{atm}^2}{P_{atm}}\ \frac{DC}{Q_{gen}}\ K_{refuse}^{refuse}\ (WD/L)_{LFG}$$

  Assuming that atmospheric pressure is equal to 1 atm and using the refuse and landfill gas properties provided in Section G.6.1, the expression becomes

  $$Rp^2 \ln(Rp/.3048) = (P_l^2 - 1)(1.7 \times 10^4)$$

  To obtain the curve in Figure 9-10, the landfill gas pressure term was modified to take into account the pressure drop across the collection/control device.

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16. ABSTRACT

This Background Information Document was developed to support EPA's proposal for New Source Performance Standards and Emission Guidelines under Section 111 of the Clean Air Act for air emissions from municipal solid waste landfills (MSW landfills). The standards and guidelines will apply to MSW landfills sized greater than 100,000 Mg of refuse in place and emit 150 Mg/yr or more annually of non-methane organic compounds (NMOC's). This document provides information for Best Demonstrated Technology recommended for the proposal as well as emission guidelines for implementation of the regulation.

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